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# Evaluation of Auxiliary Tracker Approach to Solving the EED Problem at Robins AFB, Georgia

By

T. C. Stockdale
J. K. Webb
H. Feldman
D. W. Luke

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## REVIEW AND APPROVAL

This technical report has been reviewed and is approved for publication.


DOUGLAS DUNPHY, GS-12
PAVE PAWS Project Engineer

THOMAS R. PUCCI
PAVE PAWS Program Manager
Space & Missile Warning
  Systems Program Office


FOR THE COMMANDER


JAMES E. JACOBY, COL, USAF
Program Director
Space & Missile Warning
  Systems Program Office

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Since the onset of operations of the PAVE PAWS radar at Robins AFB in Georgia, concerns have been raised regarding a possible safety hazard to aircraft due to the proximity of the radar to the airport runway. The concern is that the Electro-explosive Devices (EEDs), with which some of the aircraft are equipped, might be subject to inadvertent ignition. Various approaches are being studied to remedy this problem. Among these is the use of an auxiliary tracker to provide position information on nearby aircraft to the PAVE PAWS radar to allow it to inhibit transmissions as necessary. MITRE recommends the auxiliary tracker approach using the current or upgraded Airport Surveillance Radar (ASR) and beacon system presently located on Robins AFB be used to provide this information. This report details the study of this approach.

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# EXECUTIVE SUMMARY

Since the onset of operations of the PAVE PAWS radar at Robins AFB in Georgia, concerns have been raised regarding a possible safety hazard to aircraft due to the proximity of the radar to the airport runway. The concern is that the Electroexplosive Devices (EEDs) with which some of these aircraft are equipped might be subject to inadvertent ignition. Interim operational procedures restricting radar and aircraft operations are in effect at Robins AFB to compensate for this hazard.

Various approaches are being studied to remedy this problem. Raytheon has proposed a detection and tracking system, designated the Embedded Tracker (ET), which would be embedded in the PAVE PAWS radar itself, to detect the presence of aircraft in the vicinity of the radar, and blank individual beams, or pulses, to avoid illuminating the aircraft. At present, Raytheon is reexamining this approach to assess the risk and cost. The Air Force has also initiated studies of other approaches to minimize this risk, such as use of an auxiliary tracker, relocating the runway, relocating the site, relocating the north face, blanking the track function above 4-5°, and using a shortened pulse.

MITRE has evaluated the use of an auxiliary tracker, and the results of this study are the subject of this report. MITRE recommends the auxiliary approach using the current or upgraded Airport Surveillance Radar (ASR) and beacon system located at Robins AFB, a few miles from the PAVE PAWS radar. This approach has a cost advantage because it utilizes existing equipment. An important conclusion is that, since this radar is located a few miles away, it can provide coverage around and immediately above PAVE PAWS, whereas a radar collocated with PAVE PAWS will typically have a blind zone immediately above it in which the position of aircraft would not be known. A collocated radar must be able to search or track over essentially hemispherical coverage at very close range. This restriction does not apply to an auxiliary radar located a few miles away. Another important conclusion is that the use of both ASR and beacon data insures a high probability that detections from one or the other will be available.

Using this approach, the data obtained from the ASR and the beacon would be digitized and sent to the PAVE PAWS radar via a medium such as phone lines, fiber optic cable, or microwave link where it would be put on a separate display in the Missile Warning Operations Control (MWOC) room. The display software would provide tracking which would predict position and activate an alarm several seconds before an aircraft was predicted to be within a prescribed hazard zone about the radar. At the time the aircraft enters the zone, a control signal would then be sent to PAVE PAWS to blank either a sector of coverage or an entire face. Control would be automatic but the operator could override it if he so desired. Blanking a sector will have less impact on mission requirements than blanking a face. Whether a sector or a face is blanked will have to be decided based on user requirements.

A measurement program is also suggested, assuming it could be done at minimal cost. The primary purpose would be to verify performance, provide a basis for determining the number of aircraft penetrations per day and the appropriate blanking technique, evaluate operator requirements and the man-machine interface, and validate tracking algorithms. Measurement and testing would be done on a noninterfering basis.

The auxiliary tracker option is recommended because of its coverage, performance, availability, cost, and ease of implementation.

# ACKNOWLEDGMENTS

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# SECTION 1

# INTRODUCTION

PAVE PAWS is a surveillance and tracking radar that provides warning and attack characterization data on Sea-Launched Ballistic Missiles (SLBMs) that penetrate PAVE PAWS coverage and also provides similar data on Intercontinental Ballistic Missiles (ICBMs) that have performance characteristics similar to SLBMs. Four PAVE PAWS radars are in operation at this time. They are located at Cape Cod AFS, MA, Beale AFB, CA, Robins AFB, GA, and Eldorado AFS, TX. The radar at Robins became operational in late 1986.

In March 1983, an Environmental Assessment was completed for the proposed Robins PAVE PAWS radar [1]. For this site, Air Force plans at that time called for an initial installation of a 0-dB configuration and later growth to a 10-dB (three times the power and aperture) configuration. It was concluded that construction of this radar system at Robins AFB would have no significant impact on the environment, and it was located a little over a mile from the centerline of the approach-departure path for the Robins AFB runway (runway 32/14). Since the onset of operations of this radar, concerns have been raised regarding a possible safety hazard to aircraft due to the proximity of the radar to the airport runway. The concern is that the Electroexplosive Devices (EEDs), with which some of these aircraft are equipped, might be subject to inadvertent ignition.

Various approaches are being studied to remedy this problem. Raytheon has proposed a tracking system which would be embedded in the PAVE PAWS radar itself to detect the presence of aircraft in the vicinity of the radar and blank individual beams, or pulses, in order to avoid illuminating the aircraft. This approach would utilize four of the existing subarrays to form a beam and interleave a short-range aircraft search-and-track function in with the other radar modes. At present, Raytheon is reexamining this approach with emphasis on risk and cost along with other approaches. The Air Force has also initiated studies of other approaches to minimize this risk, such as use of an auxiliary tracker, relocating the runway, relocating the site, relocating the north face, blanking the track function above 4-5°, and using a shortened pulse.

The concept of an auxiliary tracker is to use a radar or beacon system at a nearby location to provide position information on nearby aircraft to PAVE PAWS which would allow it to blank either a certain sector of coverage or an entire face. MITRE has evaluated the use of an auxiliary tracker and the results are the subject of this report. MITRE recommends the auxiliary tracker approach using the current or upgraded Airport Surveillance Radar/beacon system located at Robins AFB, a few miles from the PAVE PAWS radar. From the standpoint of coverage, performance, availability, cost, and implementation this approach is recommended. The discussion herein is confined to the tracker requirements relative to the 0-dB PAVE PAWS. The 10-dB PAVE PAWS would have a larger hazard zone and would modify the tracker requirements.

Section 2 discusses the airport regulations and control zones, typical flight paths expected, and operations statistics. Section 3 discusses the dimensions of the area around PAVE PAWS that is designated as the hazard zone, and its location relative to the runway.

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Section 4 summarizes the aircraft and clutter environment at Robins and synthesizes a set of requirements. Section 5, then, details the approach recommended by MITRE, and discusses the performance along with other factors such as availability and cost. Section 6 describes a suggested measurement and test program, and Section 7 summarizes the conclusions.

# SECTION 2

## AIRPORT DESCRIPTION

### 2.1 CONTROL ZONES

Robins AFB is a military airport with a military-operated control tower, and has both military and civil traffic. The tower controls the Airport Traffic Area (ATA), a cylindrical volume with a 5-statute-mile radius, to an altitude of 2300 ft Mean Sea Level (MSL). Control means that a pilot must establish and maintain radio contact with the tower to enter or operate in the ATA and on the active runway. The airport is overlaid with a Terminal Radar Service Area (TRSA) which has a radial extent of 20 miles. The maximum altitude is 10,000 ft MSL while the minimum altitude starts at the surface at the airport and increases to 2500 ft at maximum range. The TRSA is operated by the FAA and is designated the Macon Radar Approach Control (RAPCON). This TRSA facility, or RAPCON, along with its ASR/beacon system is located on Robins AFB and serves both Robins and the Macon (Lewis B. Wilson) airport which is three miles to the north. Hence, at Robins AFB, the tower is operated by the military and controls the ATA while the RAPCON controls the TRSA and is operated by the FAA. The TRSA provides separation of Instrument Flight Rules (IFR) aircraft and provides Visual Flight Rules (VFR) traffic advisories. Participation by VFR aircraft outside the ATA of either airport under VFR conditions is voluntary. Pilots participate in TRSA operations by voice radio communication; however, participation is mandatory only for aircraft operated under IFR.

There is also an area at the core of the TRSA that encloses both Macon airport and Robins AFB with altitude limits from the surface to 14,500 ft which is called the control zone. This area is only active under IFR conditions. This area includes the ATAs of both airports and extensions from runways into final approach courses. The RAPCON rather than the tower is the controlling authority for the control zone. In this area, the RAPCON controls IFR traffic even under VFR conditions, and also advises VFR traffic around the field, but gives control of traffic to the tower when a VFR pilot reports the field is in sight, or when an arriving IFR pilot reaches the final approach fix.

The PAVE PAWS radar has not been officially identified as a hazard to the FAA, so the controllers disregard it in controlling flight operations. Special handling for certain arriving traffic is administered by the Robins AFB tower operators. For instance, aircraft with external stores equipped with EEDs for their release are required to file a Prior Permission Required (PPR) as part of the flight plan. Upon arrival of such an aircraft, the tower calls the PAVE PAWS radar on the telephone and requests that the radar's north face be turned off. It is not turned on again until the landing is confirmed by the tower.

## 2.2 FLIGHT PATHS

Figure 1 shows flight paths that are to be expected most of the time for both IFR and VFR operations at Robins AFB. This information was obtained from interviews with RAPCON controllers. This is a single-runway airport with runway orientation of 326.7/146.7 degrees magnetic, currently designated runway (RWY) 14 and RWY 32. It shows the paths for precision and nonprecision approaches, VFR traffic, and RWY 14 departures. It shows that RWY 14 departures are turned to a heading of 120° after takeoff. Missed approaches from RWY 32 are turned to a heading of 070°, and those from RWY 14 are turned to a heading of 100°. The partial circle shown to the southwest of the runway is the approximate outline of the hazard zone. RWY 32 has the vast majority of the traffic, but the precision approaches on this runway have little potential for overflight of the PAVE PAWS hazard zone. For instance, in the case of the precision approach using the Instrument Landing System (ILS) on RWY 32, an aircraft that has not declared a missed approach can be reliably presumed to be within less than 1.5° of the localizer course aligned on the runway center line. This angular offset does not intersect the hazard zone. In the case of a missed approach, the pilot is cleared to turn to the right, as shown in figure 1, as part of the missed-approach procedure. This ILS corridor will be discussed in more detail later. As for the non-precision approach to RWY 32, nearly all aircraft have been observed to fly to the right of the extended runway centerline. While equipment accuracy values indicate a possibility of penetrating the hazard zone, few or none have been observed to the left of the centerline. Of the paths shown in figure 1, only the VFR arrivals from the west landing on RWY 32 have a high potential for flight through the hazard zone, and, in fact, this would be limited primarily to transient arrivals not familiar with the procedures. The VFR aircraft are worked by the RAPCON until they have the field in sight and then are handed off to the tower. It is likely that most pilots simply choose the distance from the runway where they will turn to the final leg and fly to that point. Neither the RAPCON nor the tower advises the pilot of the PAVE PAWS hazard. The Automatic Terminal Information System (ATIS) broadcasts contain no warning of the hazard.

The traffic on airway V-362 passing west of the field has some potential for flying through the hazard zone, but this is difficult to quantify. The outer edge of the airway does overlie PAVE PAWS. Airways are 8 nmi in width and the Minimum Enroute Altitude (MEA) is 2000 ft. Since the hazard zone extends to 4100 ft above PAVE PAWS, it does extend into this airway. However, there is uncertainty as to the amount of traffic on this airway. It does seem to avoid medium- or high-density hubs, so it may not add substantially to the total number of penetrations.

A situation which can cause aircraft to fly through the hazard zone was observed in March 1990. The operations are depicted in figure 2. The wind was from the southeast quadrant, which resulted in RWY 14 being active. Macon RWY 13 (shown in figure 2 crossing RWY 5 at Macon) was also favored because of the wind, but RWY 5 was selected
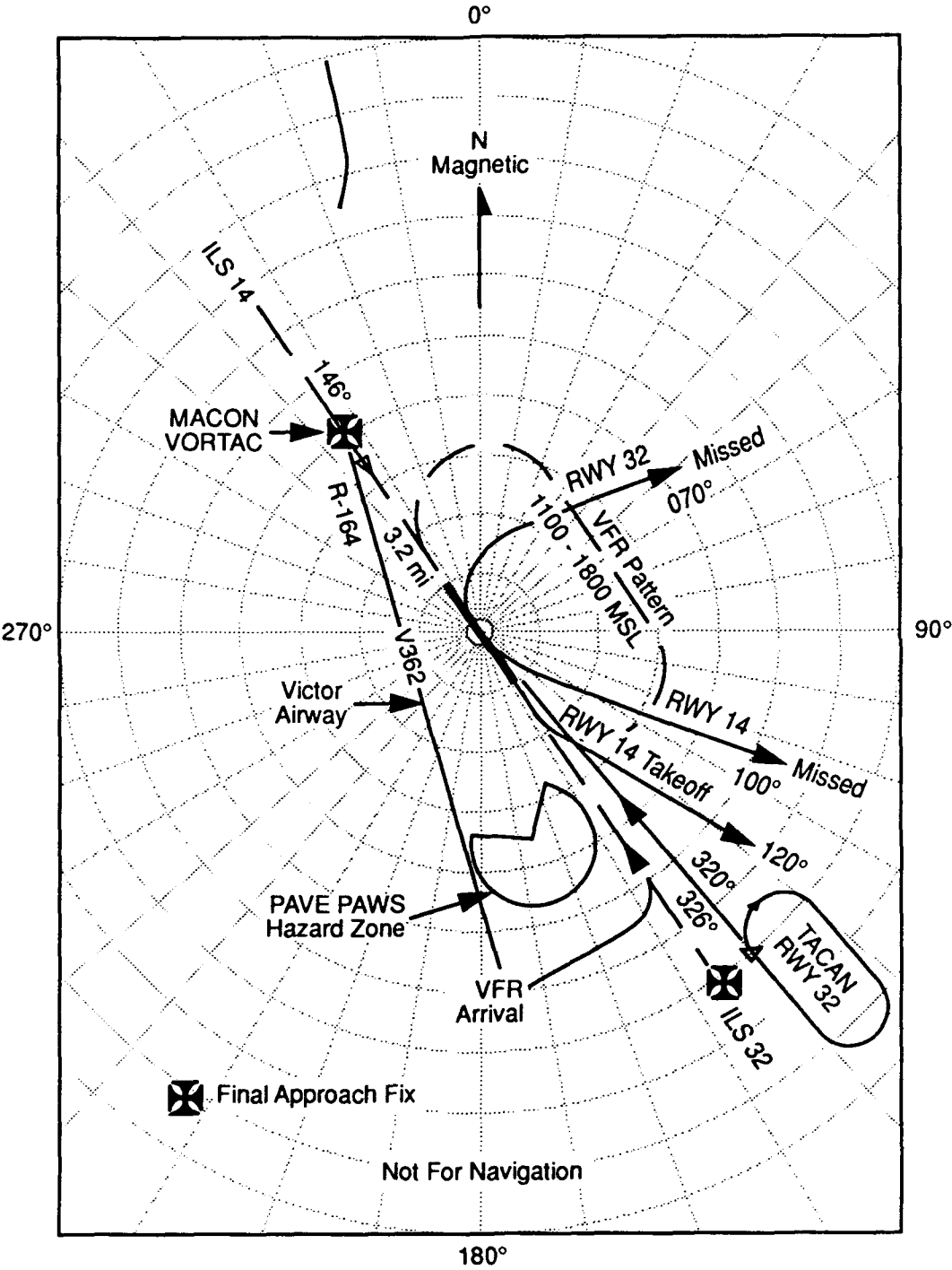
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Figure 1. Flight Paths Expected for Robins AFB
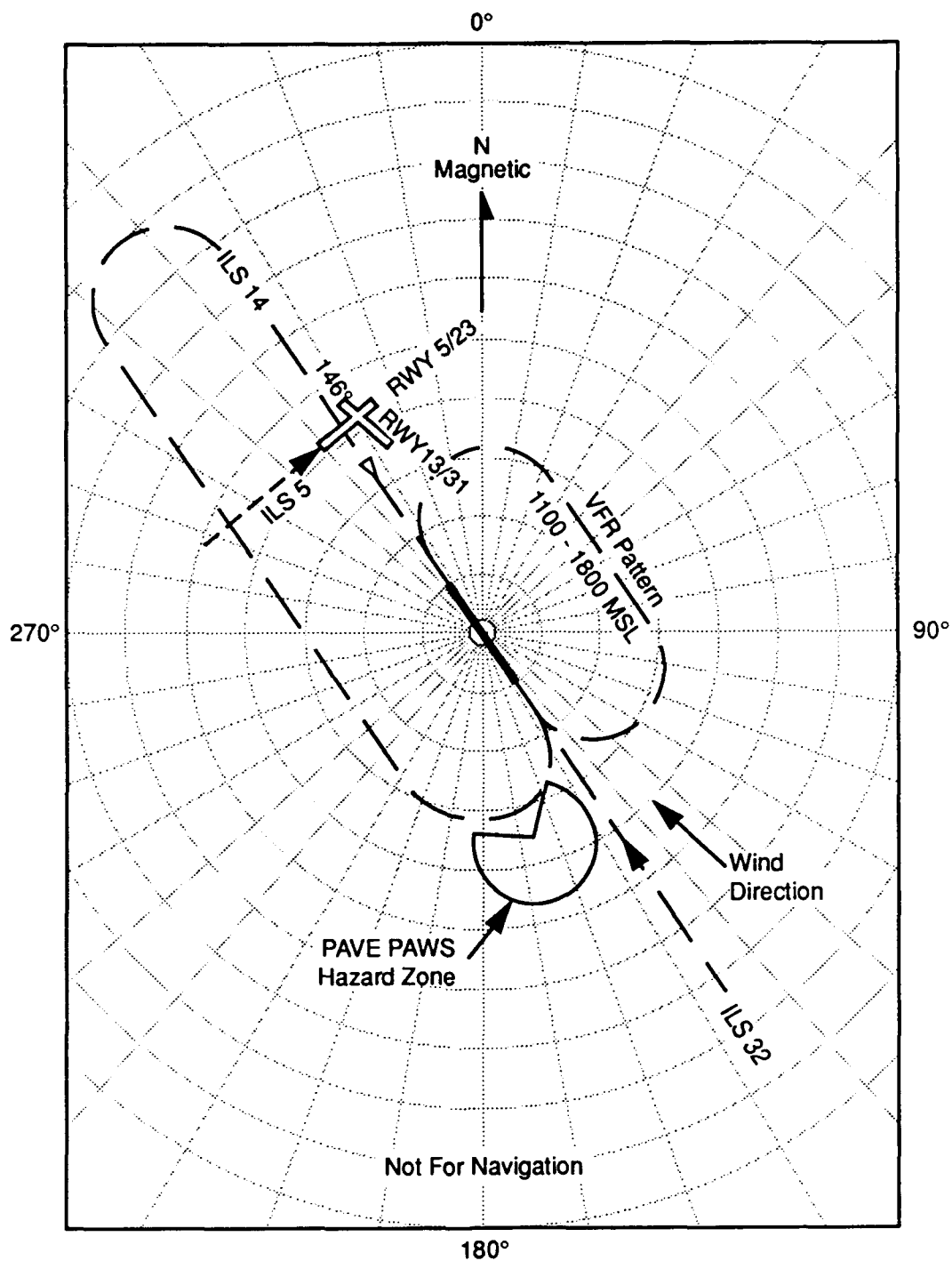
Figure 2. Observed Runway 14 Flight Paths for Robins AFB

because RWY 13 departures from Macon would conflict with Robins RWY 14 approaches. But, because RWY 5 was chosen, the IFR pattern at Robins had to be located west of the field as shown in the figure. If the Robins IFR traffic were located east of the field it would conflict with Macon RWY 5 departures. The result was that in a short space of time two aircraft were observed to turn to the right nearly over PAVE PAWS while climbing to an altitude of 2,600 ft. This wind condition is not unusual; 30-year wind data indicates that RWY 32 will be active with no more than a 4-knot tailwind 82 percent of the time. When the RWY 32 tailwind exceeds 4 knots, RWY 14 becomes active with that wind as a headwind; this is estimated at 18 percent of the time.

At present, the warning to pilots to keep clear of PAVE PAWS is contained in the DOD Flight Information Publications IFR supplement which can be summarized as follows:

Aircraft are cautioned to avoid PAVE PAWS by 1 nmi at and below 6400 ft. VFR traffic arriving on RWY 32 are to remain on or right of the extended centerline from 4 nmi to 1 nmi. VFR traffic departing RWY 14 are to remain on or left of extended centerline until 4 nmi out. Aircraft with external jettisonable stores are required to file a Prior Permission Required (PPR) request with their flight plan [2].

Upon arrival of such aircraft, the tower calls PAVE PAWS on the telephone and requests that the north face of the radar be turned off. Upon landing, the tower again calls to permit the radar's reactivation. This results typically in 2-3 hours downtime per month.

## 2.3 OPERATIONS STATISTICS

Statistics were obtained on the number of operations from the FAA RAPCON and from the Robins AFB Tower, or Base Operations. The FAA keeps statistics by saving flight strips for two years. Flight strips are the paper tickets that are either distributed as flight plans or are locally generated by controllers for each operation. Operations are IFR or Stage III (VFR traffic advisories). Table 1 lists statistics obtained from the RAPCON for 1989. The RAPCON operations include MACON as well as Robins, so the latter is broken out separately. These operations break down into the two categories of VFR and instrument operations. The missed approaches are FAA estimates, and are not based on recorded data. The statistics obtained for the Robins tower operations for 1989 are given in table 2. They are different from the RAPCON statistics of table 1 in that different measurements are used for tower operations. For example, IFR and VFR arrivals and departures are worked by both, and each scored as an operation by both, while VFR pattern operations are worked only by the tower, and appear only in the tower statistics. Also, IFR and VFR arrivals and departures between 0000 and 0600 local time appear only in tower statistics because the RAPCON is closed during those hours. In addition to the basic breakdown between IFR and VFR operations, this table also shows the separation by operator type and by time of day.

An additional source of statistics is the Transient Alert office at Robins AFB. This office has a count of aircraft that arrive from other bases that eventually depart to return to their bases. They are included within tower and RAPCON statistics as arrivals and departures. These are shown at the bottom of the table, but are included in the total.

It would be desirable to accurately estimate the number of aircraft per unit time that would normally penetrate the hazard zone. This would aid in determining the most cost-effective blanking technique. If the frequency of penetration is low, a simple form of blanking could be used, such as face blanking. On the other hand, if the number of penetrations is high, then a more sophisticated technique which blanks a specific small sector of beams would be necessary in order to minimize mission impact. Although the operation statistics give the number of operations in different categories, this does not provide the detail as to the exact flight paths used. Observations or measurements of the actual flights made over a period of time would help to quantify the number of penetrations, but the existence of restrictions or Interim Operational Workarounds (IOWs), which presently limit the operations would require that any such measurements be extrapolated to the conditions where these IOWs were removed, and this would limit the usefulness of the measurements. Based on the data in tables 1 and 2 as well as personal observations and discussions with RAPCON personnel, the estimate of the number of penetrations is about three to four per day with the present restrictions in place, and could be two to three times higher if all restrictions were removed. Assuming an average of one minute in the hazard zone per penetration, three to four penetrations per day would correspond to three to four minutes downtime per day, respectively. For this number, simple face blanking would be sufficient, while if the number is much higher, sector blanking would probably be required in order to avoid a substantial impact on the mission.

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## Table 1. RAPCON Traffic Statistics for 1989

| | |
|---|---|
| Total RAPCON Operations (1) | 165,888 |
| Total Robins AFB Operations | 38,901 |
| VFR/Stage III Operations | 17,296 |
| Instrument Operations Robins AFB | 21,605 |
| Instrument Approaches (2) | 759 |
| Missed Approaches (3) (Estimated) | 25 |

(1) Both Robins AFB and Macon
(2) Included in Instrument Operations
(3) Included in Instrument Approaches

**Table 2. Robins AFB Tower Traffic Statistics 1989**

| | |
|---|---|
| Total Robins AFB Tower Operations | 56,165 |

Separated by VFR/IFR

| | |
|---|---|
| VFR Local | 18,590 |
| VFR Itinerant (1) | 6,463 |
| IFR Arrivals | 14,974 |
| IFR Departures | 16,138 |

Separated by Operator Type

| | |
|---|---|
| Military | 47,030 |
| General Aviation/Civil | 6,066 |
| Air Carrier/Taxi | 3,069 |

Separated by Time of Day

| | |
|---|---|
| 0000-0600 | 1,556 |
| 0600-1200 | 16,680 |
| 1200-1800 | 27,330 |
| 1800-2400 | 10,599 |
| Transient Aircraft (2) | 6,761 |

(1) Itinerants are radio contacts with transitioning aircraft that may not operate in the ATA (tower airspace).

(2) Transient aircraft are included in total and separated operations.

# SECTION 3

## HAZARD ZONE DESCRIPTION

The criterion for the hazard limit applied here is the 100 watts per square meter prescribed by Air Force Regulation 127-100 [3]. This level has been verified by ASD as reasonable, based on a review of testing done at the Naval Weapons Laboratory at Dahlgren, Virginia. Based on these tests, the level is quite conservative. Most EEDs require about 100 times this power level to actually ignite the EED, with the most sensitive one requiring about 8 times this level [4].

## 3.1 PLAN VIEW OF HAZARD ZONE AND RUNWAY

Figure 3 gives a plan view showing the dimensions of the hazard zone and the distances from the runway centerline and ILS corridor. This is a single-runway airport. For aircraft coming from the south, the runway is designated 32, and for those coming from the north, it is designated 14. As shown here, the center of PAVE PAWS is 6912 ft from the centerline of the runway.

The distance 912 ft from the centerline represents the limits of the ILS corridor corresponding to the maximum 1.5° deflection. The hazard zone can be thought of as cylindrical up to a height where it becomes dome shaped. This shape will be shown in a side view later. Along this contour, the power density is calculated to be 100 watts per square meter, maximum. The point on this contour closest to the runway comes to within 1512 ft of the centerline of the runway and 600 ft from the limits of the ILS landing corridor. The limits of the landing corridor represent the maximum errors and the probability that an aircraft on an ILS approach will be outside these limits is quite low. The value of peak power density is calculated as

$$R = \left[ \frac{P_t \, G_t}{4\pi \, P_f \, L_a \, L_s} \right]^{\frac{1}{2}}$$

Where

$R$ = The hazard range in meters

$P_t$ = Peak power into radiating elements
= 1792 active elements x 340 watts/module
= 609,280 watts

$G_t$ = Transmit antenna gain = 38.36 dB

$P_f$ = Power density = 100 watts/square meter

$L_a$ = Array transmit losses = .5 dB
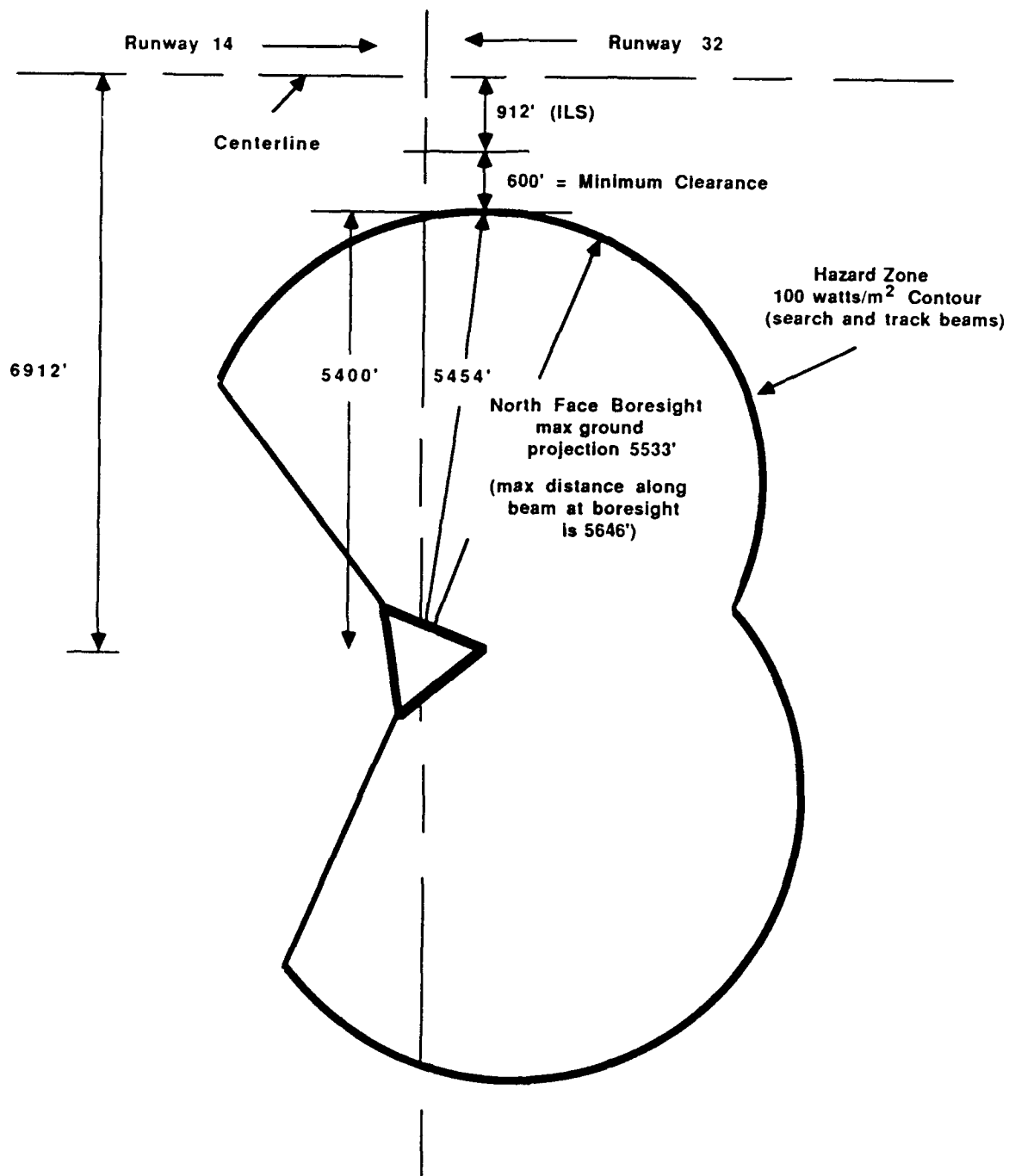
$L_s$ = Scan loss = 0 at boresight

Figure 3. Plan View of Hazard Zone and Runway

The hazard range calculated for these values at boresight (no scan loss) is 5646 ft. For the phased array, there is a scan loss as the array is scanned off boresight. This scan loss is proportional to the reduction in projected aperture in any direction which can be represented, as a conservative approximation, by the cosine of the angle off boresight. As shown in figure 3, the distance to the point closest to the runway is reduced by scan loss to 5454 ft. from the radar which leaves 600 ft. from the edge of the hazard zone to the edge of the ILS corridor.

The values used for peak power per module, transmit gain, and array losses have been based on measured values. Also, the calculated value of hazard range was checked against values obtained during tests conducted in 1987, the results of which are given in references 6 and 7. One of these tests was conducted at the PAVE PAWS site 3 facility at Robins AFB, using a helicopter. The resulting power density as a function of range in the boresight direction is reproduced here in figure 4. From this data, the hazard radius is seen to be 5600 ft., which is sufficiently close to the above calculated value to be within the measurement tolerance. A similar series of tests was conducted at PAVE PAWS Site 2 facility at Beale AFB. In this case, a tower was erected 1726 ft. from the north face in the boresight direction. The resulting power density, as a function of height along the tower, is reproduced here in figure 5. The maximum density, corresponding to the peak of the beam, is seen to lie between 210 and 220 ft. in height and the peak power density in that direction is about 1000 watts/ square meter. Extrapolating to 100 watts/square meter, the range is found to be 5458 ft. as compared to the value calculated above 5646 ft., which indicates that the calculations are conservative.

## 3.2 SIDE VIEW OF HAZARD ZONE

Figure 6 is a side view of the hazard zone looking toward the runway from the south as if landing on runway 32. It shows the hazard area and the relationship between the ILS corridor and the surveillance fence beam. The limit of the hazard area is shown as a vertical line at the point closest to the runway. The limit of the contour is constructed assuming the beam could be pointed in any direction in elevation. This would be the case if the beam were scanning in elevation, such as in track. Superimposed on this contour is the surveillance beam, at the nominal elevation angle of 3°. This beam normally scans azimuthally only at this elevation angle. However, there are occasions when search beams are above this position. For instance, some search beams are raised momentarily, once in the morning and once in the evening, as a sun avoidance procedure. Or some beams may be raised at times to acquire unknown satellites. Also, of course, track beams appear above this position. Beams are never below this position. Also shown are the limits of the ILS contour in height as well as in width. This illustrates that an aircraft landing in the ILS pattern will be above the nominal position of the surveillance beam. Of course, at higher elevation angles the range decreases and the contour becomes a dome as shown in figure 7. Figure 7 presents the same view as figure 6, with a contracted scale showing the zone's uppermost extent.
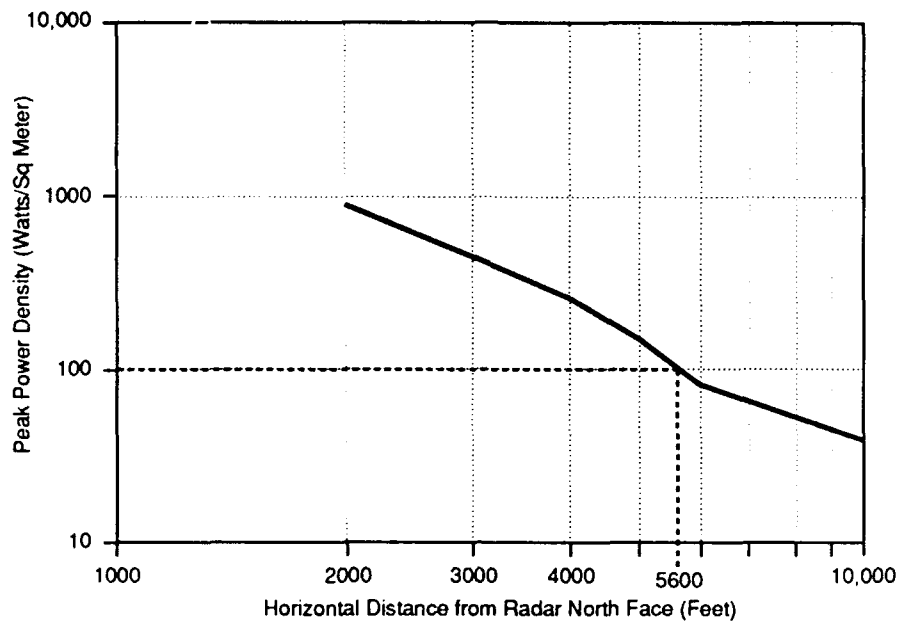
Figure 4. Peak Power Density versus Distance
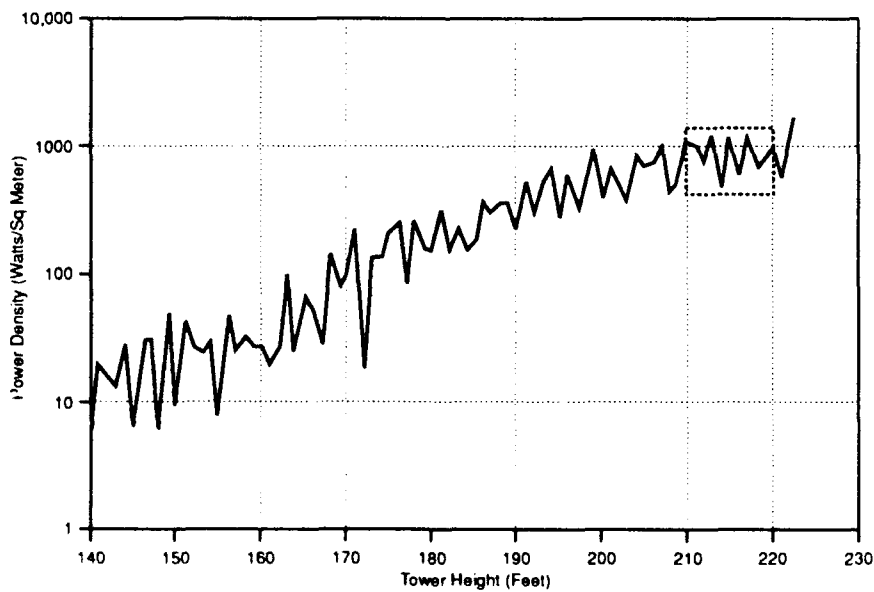
Figure 5. Peak Power Density versus Tower Height, Normal Radar Mode

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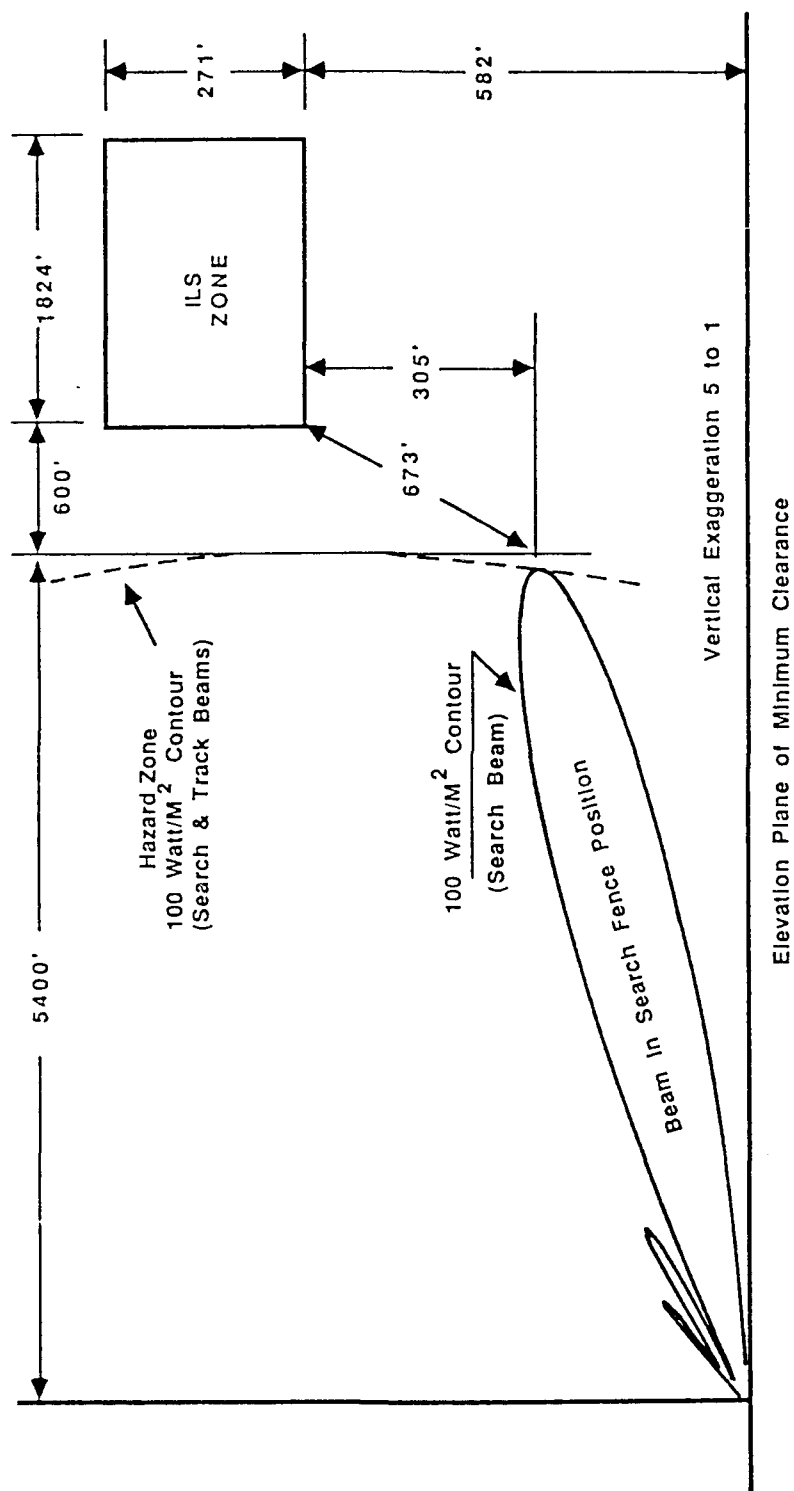
Figure 6. Runway View and ILS Corridor Showing Search Beam

Hazard Zone
100 Watts/M² Contour
(Search and Track Beams)

5400'

4267'

Elevation Plane of Minimum Clearance

ILS Zone
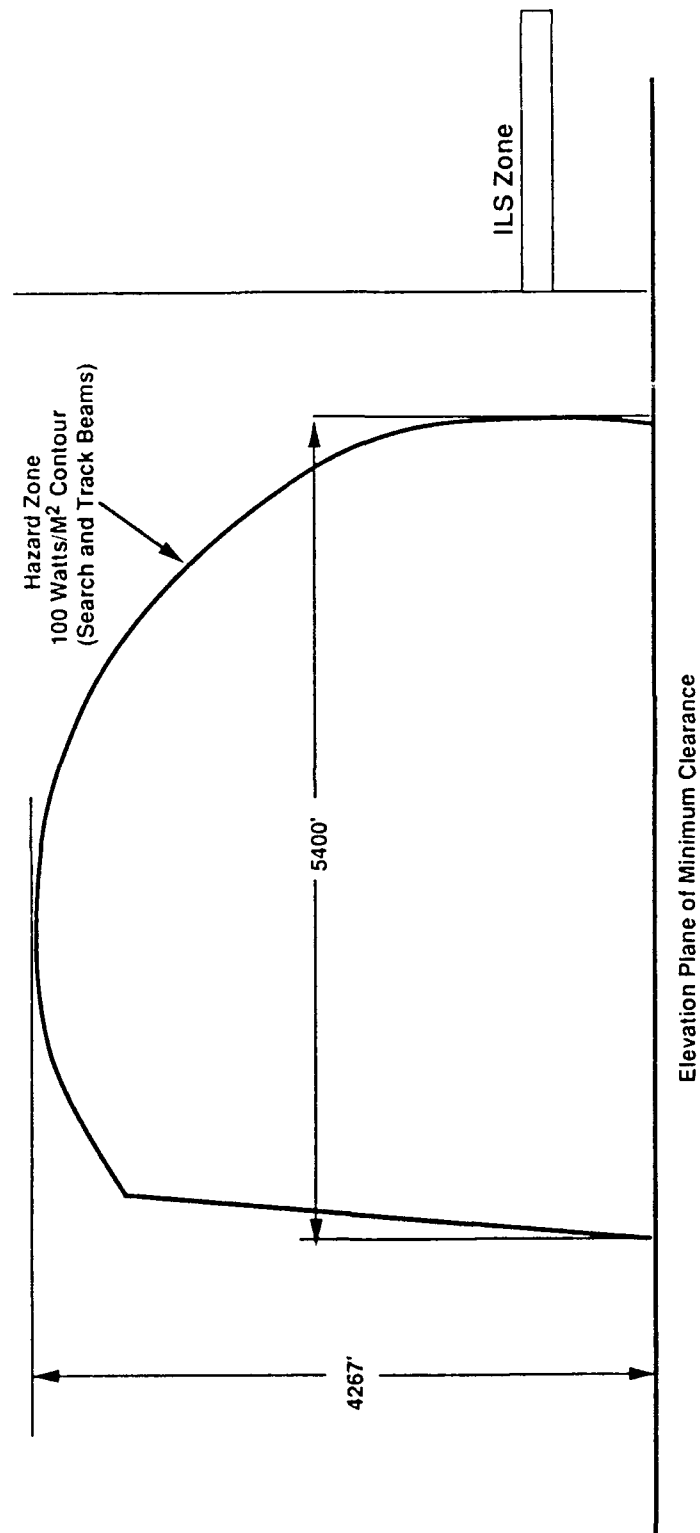
Figure 7.  Runway View Showing Height of Hazard Zone

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# SECTION 4

# REQUIREMENTS

This section gives requirements which follow from the previous discussion as well as other discussions with Robins AFB personnel. They apply to any tracker used to provide aircraft position information, whether the system is collocated with PAVE PAWS or located separately. Table 3 gives the aircraft and clutter environment from which the tracker requirements are derived. The top part gives the general nature of the aircraft expected including speed size and expected altitude regime. It is important to note that aircraft can approach from any direction and that they could affect either face. Also, they could only be a few hundred feet above the radar. The clutter environment must be considered for any sensor relying on the skin echo. This will not be a concern for a beacon. Table 4 gives other more direct requirements. Perhaps the most important is to obtain a high probability of detection. It is also important to have a low false alarm rate to insure that the radar is not unnecessarily interrupted. Again, based on the previous predictions that the radar may be interrupted about three to four times per day, the false alarm rate should be less than one per day. The availability should be sufficiently high that it does not materially degrade that of the radar itself which is .98. The blanking is in a sense an interface requirement. It could take the form of either face blanking or sector blanking. Blanking the face would require only turning off the RF drive while sector blanking would require interfacing with the software. The remaining requirements are also important but are difficult to quantify, and no specific value is assigned to them.

## Table 3. Aircraft and Clutter Environment

Aircraft Environment

    Military and civilian, including large transports, fighters, and helicopters

    Speeds in vicinity of hazard zone—50 to 180 knots

    Typical turn rate in vicinity of hazard zone—.5 G

    Highest authorized speed below 6000 ft. (highest extent of hazard zone)—250 knots

    Most aircraft below 2000 ft—helicopters as low as 300 ft

    Aircraft can approach hazard zone from any direction

    Aircraft near hazard zone may be in front of either face and may transition from one face to another

    Number of aircraft within 5 miles of PAVE PAWS at any one time—10

    Minimum aircraft radar cross-section (skin echo)
        $1 \ m^2$ nose-on aspect
        $10 \ m^2$ side aspect
        Swerling I (Rayleigh) fluctuation

Clutter environment

    Terrain reflectivity (woods and cultivated land)— -42 dB

    Rain rate—very heavy, 40 mm/hour

**Table 4. Tracker Requirements**

Probability of detection of any aircraft at or in hazard zone—.9999
with a goal approaching unity

Number of false penetration reports —< 1 per day

Availability >.996

Minimal impact on mission performance

Minimal site activation and test downtime

Minimal cost

# SECTION 5

## PROPOSED AUXILIARY TRACKER OPTION

The approach suggested here to meet the requirements is to use the Airport Surveillance Radar (ASR) and its associated beacon system which are presently located on Robins AFB. The data obtained from these radars would be digitized and sent to the PAVE PAWS radar where it would be put on a separate display in the Missile Warning Operations Control (MWOC) room. The display would have a map which would include the boundaries of the PAVE PAWS hazard zone. Targets would be displayed similar to the way they are displayed to an air traffic controller. The display software would provide processing which would make a prediction for a few seconds ahead and activate an alarm if an aircraft was predicted to be in the hazard zone. It would also provide a signal which could be used to turn off the appropriate face. This would be done by disabling the drive to the face which is the way it is done now. This assumes that the current flight restrictions remain in place, so that the number of penetrations remain at three to four per day as discussed in Section 3. The control would be automatic but an operator could immediately override this control if he so desired. The alarm would sound until the intruding aircraft had flown out of the area. The face would automatically turn on again (if the off signal had not been overridden).

### 5.1 Main Features of Approach

This ASR (sometimes referred to as the primary radar) and beacon (sometimes referred to as the secondary radar) equipment is located in the RAPCON facility near the runway and about 5 nmi from PAVE PAWS. Table 5 gives some of the features of this approach which make it attractive. First of all, the ASR/beacon system uses already existing equipment presently maintained by the FAA, resulting in minimal cost. Since it is about 5 nmi from PAVE PAWS, it can provide good coverage in that it can see all around this radar as well as directly above it. Since it is a separate system, the interface with PAVE PAWS can be fairly simple, resulting in minimal time to implement. Other features derive from the fact that these systems are specifically designed to provide reliable information on aircraft at the terminals. For instance, the system makes use of the information from both the ASR and the beacon to obtain the maximum amount of information on the aircraft. Also, the ASR can see targets at low velocity. Moreover, its location is such that departing aircraft and aircraft on final approach present a high radial component of their velocity to the radar. The beacon system can see aircraft even though they may be standing still. Also these systems have built in redundancy and hence a very high availability. The characteristics of these systems will be discussed in more detail later.

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**Table 5. Features of Proposed Approach**


- Utilizes Existing Radar/Beacon System

- FAA Provides Maintenance

- Low Cost

- Good Coverage

- Minimum Site-Activation Downtime

- Beacon Information Available

- Good Low-Velocity Visibility

- High Radial Velocities in Final Approach or Takeoff

- High Availability

- Common Information for Use with Back-Up Procedures

The RAPCON operation controls the air traffic for the Robins AFB as well as for the Macon airport about 3 nmi to the north. There is a weather radar at Macon, but no traffic control radar. The RAPCON is manned 16 hours per day by four controllers and two maintenance people and their supervisors. It is not manned at night between midnight and 8:00 a.m. because traffic is light. Any traffic at night is controlled by the Atlanta Airport Radar Traffic Control Center (ARTCC), about 80 nmi to the north. However, the radar is left on so the information from it would still be available to PAVE PAWS. The ASR used is the ASR-5E, although it uses a later model ASR-7 antenna. Although highly reliable, the radar is quite old and is to be replaced with an ASR-8 late in 1992. The beacon is the Air Traffic Control Beacon Interrogator (ATCBI-4). The two are collocated with each other in the same facility within a few hundred ft. of the RAPCON. The interrogator antenna is located on top of the ASR antenna.

The availability achieved by these radars over the past year is quite high and the personnel there feel it can be made even higher. The only time the radar has to shut down completely is when the antenna itself is checked. This a routine operation done on a scheduled basis about every six months, and takes 2-3 hours.

If it is decided to upgrade this system using an ASR-9 this would also meet the requirements. The ASR-9 is the latest version of this radar type; it is designed for unattended operation and has improved tracking performance.

## 5.2 ASR AND BEACON RADAR DESCRIPTION

The main parameters of the ASR and beacon radars are given in table 6 [5]. First, a word should be said about the differences between them. The ASR relies on the skin echo from an aircraft to obtain position. As a result, it requires a considerable amount of power to overcome the losses both to and from an aircraft. Also, the power returned is a function of the aircraft size and aspect angle to the ASR. Further, the echo contains returns from "clutter" in the vicinity of the target, such as that from the ground, and the radar must distinguish these from the aircraft. The ASR, can do this by using Moving Target Indication (MTI), which cancels the fixed clutter to a degree, and allows it to see an the aircraft if it is moving relative to the ASR. The ASR has a broad elevation (fan) beam so it obtains azimuth and range information but not elevation information on the aircraft .

As for the beacon, it utilizes a transponder aboard the aircraft. The beacon system uses an interrogator which transmits a pair of pulses with the spacing between them indicating the information desired of the transponder, that is, identification, altitude, etc. Since there is only a one-way loss, there is not as much power required of the interrogator as there is of the ASR. Also, the the transponder return signal is on a different rf frequency so its return doesn't compete with clutter returns from the interrogator pulse. If asked to do so, the transponder can respond with altitude, so the beacon system can obtain this along with azimuth and range. The ASR has a minimum range of about .2 nmi which is set by the pulse length, whereas the beacon is not limited by the pulse length because the transponder reply is separated by a known delay. In this case, where the ASR radar is located about 5 nmi from PAVE PAWS, the minimum range is not a limitation. It would be for a radar collocated with PAVE PAWS. Both radars use a fan beam which yields an azimuth and a range position on an aircraft. The

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fan beam has enough elevation to easily cover the area above the PAVE PAWS radar. About the same range and azimuth accuracy can be obtained from either radar. The transponder characteristics shown are typical of most transponders. Many of the characteristics, such as beamwidth and accuracy, are not applicable, and are designated NA.

# Table 6. ASR and Beacon Radar Characteristics

| | | ASR-5 | BEACON INTERROGATOR ATCBI-4 | TRANSPONDER APX-64 |
|---|---|---|---|---|
| Operating Frequency | Mhz | 2700-2900 | 1030 (Trans) 1090 (Rec) | 1090 (Trans) 1030 (Rec) |
| Instrumented Range | nmi | 60 | 300 | 300 |
| Minimum Range | nmi | .5 | 0 | 0 |
| Pattern Shape | | Fan Beam | Fan Beam | Omni |
| Beamwidth Azimuth | deg | 1.5 | 2.35 | NA |
| Elevation | deg | 0 to 30 | 0 to 40 | NA |
| Azimuth Coverage | deg | 360 | 360 | 360 |
| Polarization | | Vert/Circ | Vert | NA |
| Accuracy Range | nmi | .125 | .125 | NA |
| Azimuth | deg | .176 | .176 | NA |
| Peak Power | kw | 425 | .24 | .5 |
| PRF | | 710-1200 | 400 | 400 |
| Average Power | w | 425 | < 1 | < 1 |
| Antenna Gain | dB | 34 | 21 | 5.5 |
| Pulse Width | usec | .833 | .8 | .8 |
| Cancellation Ratio | dB | 30 (1) | NA | NA |
| Availability Each Unit | | .9991 | .9988 | .988 |
| Combined (Int & Trans) | | NA | .987 | |
| Overall | | | .99999 | |

(1) For the ASR-8 the Ratio is 34 dB

Note that both the ASR-5 and the ATCBI-4 have very high availability [6]. This is because both have built in redundancy. Unfortunately, the transponder availability is relatively low. It is based on information obtained for a variety of transponders used on military aircraft. This limits the overall availability achievable for the beacon system, considering it as the product of that for the interrogator and transponder, to .987. However, the overall availability of the ASR and beacon (including the transponder), considering that either can provide the desired information, can be considered as

$$A = 1 - ((1 - Aasr)(1 - Ab))$$

Where Aasr and Ab are the availability of the ASR and beacon, respectively and this is essentially unity. This is the advantage of having both of these systems available.

## 5.3 SEARCH COVERAGE AND PROBABILITY OF DETECTION

Figure 8 gives a plan view showing the ASR/beacon coverage of PAVE PAWS. Being about 4.5 nmi away, it is well located to see completely around and above PAVE PAWS. As such, it can see aircraft approaching PAVE PAWS from any direction. The figure gives some examples of directions from which aircraft may be expected to approach the hazard zone. For instance, an aircraft approaching from the rear (from behind the faces) would easily be seen well before it entered the hazard zone. Of course, the ASR/beacon is particularly well situated to see aircraft leaving on RWY 14 or approaching on RWY 32. Aircraft with a beacon can be seen even when they are standing still on the runway and they can be seen by the ASR as soon as they begin to move even before they have left the ground. Hence they would be seen by either the ASR or beacon before they entered the hazard zone, even if they turned toward it on takeoff and were at low altitude.

Since the targets of interest are short range the probability of detection is quite high. A summary of probability of detection calculations for a single scan at a range of 10 nmi is shown in table 7. This is quite conservative because, normally, several scans will be available for detection. This range value allows detection of an aircraft 5 nmi on the other side of PAVE PAWS in the opposite direction from the ASR/beacon. This should be entirely adequate. The detailed calculations are given in the appendix. The signal-to-noise ratio (S/N) is quite high and over 20 hits are obtained on each scan as the beam sweeps by the target. Since it is based on the skin echo, a 1-square-meter target is used for the ASR. The beacon has the advantage that is not dependent on target size. This high S/N allows the false-alarm-rate due to noise to be kept low. For the ASR the detection probability is limited by the signal-to-clutter ratio (S/C). For purposes of false-alarm-rate calculation it is assumed that data is accepted from the sector shown by the two lines emanating from the ASR/beacon encompassing PAVE PAWS and extending to 10 nmi beyond it. Of course, the coverage need not be limited to this because the ASR/beacon covers 360° and extends for at least 60 nmi. This will provide an adequate number of hits on aircraft approaching PAVE PAWS from any direction, while minimizing the number of false reports due to noise. Also false clutter returns are minimized in the ASR by limiting the sector in this way and by using MTI. The use of tracking algorithms further reduces the possibility of generating false reports from noise or clutter. It is expected that the use of these techniques will reduce the occurrence of false reports from noise or clutter to less than one per day.
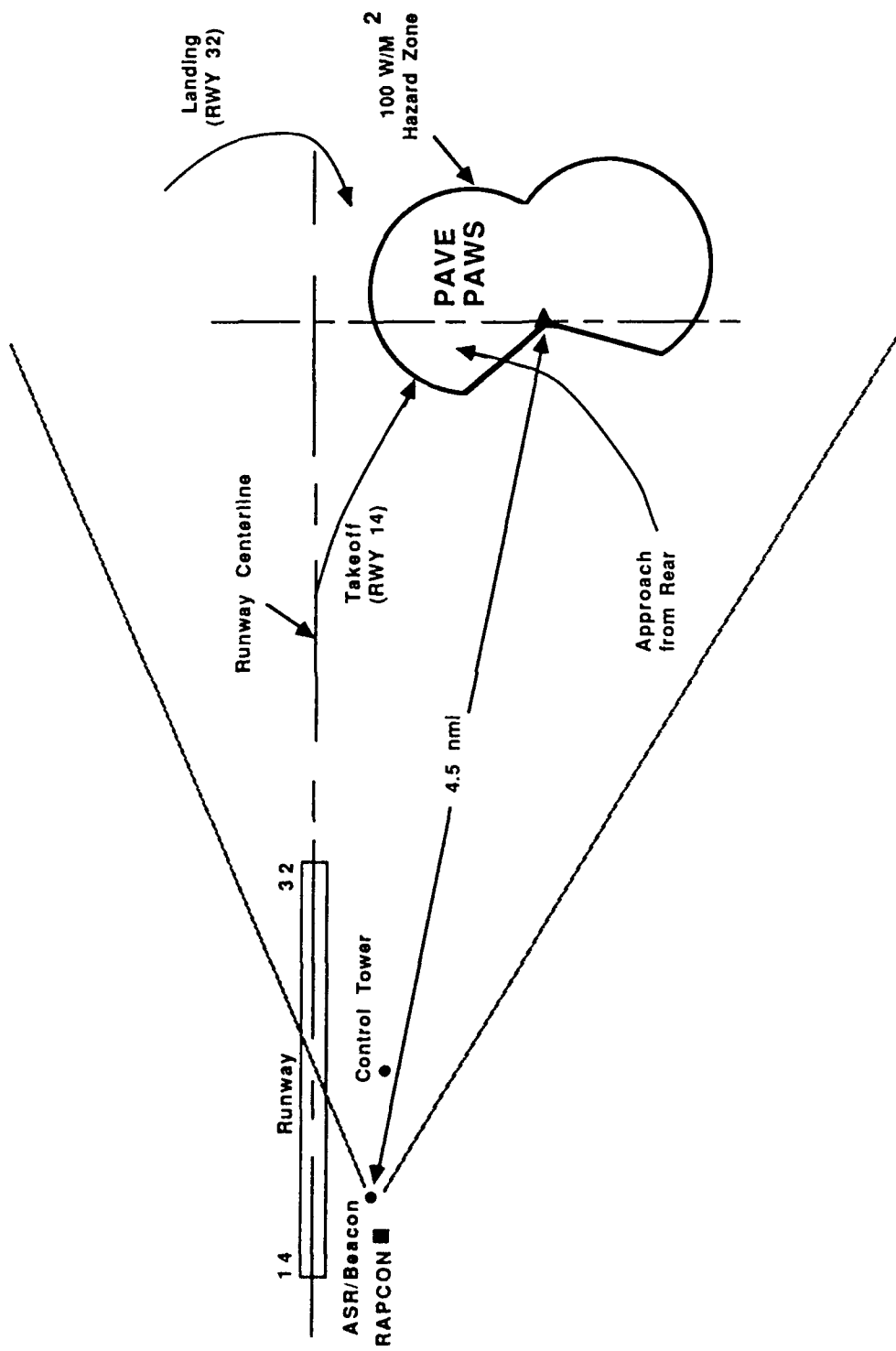
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Figure 8. ASR/Beacon Coverage of Pave Paws

**Table 7. Sensitivity Summary**

| | ASR-5 | BEACON | |
| --- | --- | --- | --- |
| | | Downlink | Uplink |
| Signal-to-noise ratio per hit | 28 | 40.9 | 33 |
| Signal-to-clutter ratio per hit | 28.2 | NA | NA |
| Number of hits per scan (1) | 25 | 28 | 28 |
| Target size (SW I) | 1 m$^2$ | NA | NA |
| False alarm rate | 10$^{-10}$ | NA | NA |
| False alarms per day | < 1 | < 1 | < 1 |

Probability of 'e :ction (single scan)
Noise li· uted .997 .999
C ir .ned (one or the other
oi both) .9999

Clutter limited .90 .999
Combined (one or the other
or both) .9999

(1) Noncoherent integration

For the beacon, the target size is not applicable since the return is generated by a transponder in the aircraft. Also, for the same reason, clutter returns are not present. The probability of having a false report due to noise is very remote because on the uplink or downlink discrete sets of pulses are used which have a particular length and spacing, and the probability that noise impulses would be mistaken for these discrete codes is very low. More appropriate in the case of beacon systems is the fruit rate, or possibility of garbling, or of ghosts due to reflections from nearby buildings. The fruit rate is a function of the number of aircraft in the area that are interrogated by other beacon systems. Since, in this area, the number of aircraft is expected to be quite low, the fruit rate and possibility of garbling is expected to be less than one per day. Also, observations made thus far have indicated that ghosts do not appear in the hazard zone.

Since the probability of detection for the ASR, and particularly for the beacon, is quite high, the combined probability that a detection is obtained from either the ASR or beacon is

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essentially unity. Again, as was done with availability, since either can provide the desired information, the combined probability of detection can be considered to be

$$P = 1 - ((1 - P_{asr})(1 - P_b))$$

where Pasr and Pb are the probability of detection of the ASR and beacon, respectively. The resultant probability is essentially unity even for the clutter-limited case.


## 5.4 TRACK ACCURACY AND PREDICTION TIME

Tracking is employed to continually monitor the position of all aircraft in and around the hazard zone. The location of the ASR/beacon enables it to continually monitor aircraft even though they are at low altitude immediately above the PAVE PAWS radar. This provides positive identification of aircraft at all times. Also, tracking minimizes the occurrence of false alarms. At least two hits are required to initiate a track, and this prevents the generation of a false penetration report based on a single isolated hit. The position of aircraft is predicted several seconds ahead. If face blanking is employed, this consists simply of a prediction of when the aircraft will enter the hazard zone. If more sophisticated blanking is required, such as sector blanking, then the prediction serves to project when and where a particular sector is to be blanked. If altitude information from the beacon Mode C is available, this input can also be used to blank a sector in elevation as well as azimuth.

The scan, or revisit, time of the ASR/beacon system is five seconds, so it is necessary for the tracker to predict ahead, at least up to this time, beyond the last of the previous hits. Since an aircraft can make a turn or maneuver during this period, this must be taken into account in the prediction. This is shown pictorially in figure 9 for aircraft taking off on RWY 14. This region ahead of it is a wedge or mushroom shape representing possible positions with the next five seconds based on a maneuver in either direction. Normally, if the aircraft is near the runway centerline, this wedge will not intersect the hazard zone. For instance, for a constant velocity of 180 knots, (303 ft. per second) the length of the wedge for a 5-second prediction would be 1515 ft., and for a .5-G turn in either direction the wedge would have a maximum width of 400 ft., or 200 ft. each side of a straight line drawn through the path of the aircraft. For a 1-G turn the width would grow to 800 ft., or 400 ft. each side of the path.

Since, as indicated in section 4, the hazard zone at its closest point is 1512 ft. from the runway, this uncertainty prediction would not come near the zone, assuming the aircraft was near the centerline of the runway as it normally would be. Hence, for a typical takeoff there should not be an intersection with the hazard zone. If the aircraft is likely to have some straight-line acceleration, this must be taken into account, although this will typically be small. For instance, for a 5-knot-per-second straight-line acceleration, the aircraft would be only about 105 ft. further after 5 seconds than it would be for the constant velocity of 180 knots (a distance of 1620 ft. rather than 1515 ft.). Hence, this has little effect on the prediction requirement. Of course, for an aircraft approaching the zone, as shown to the right
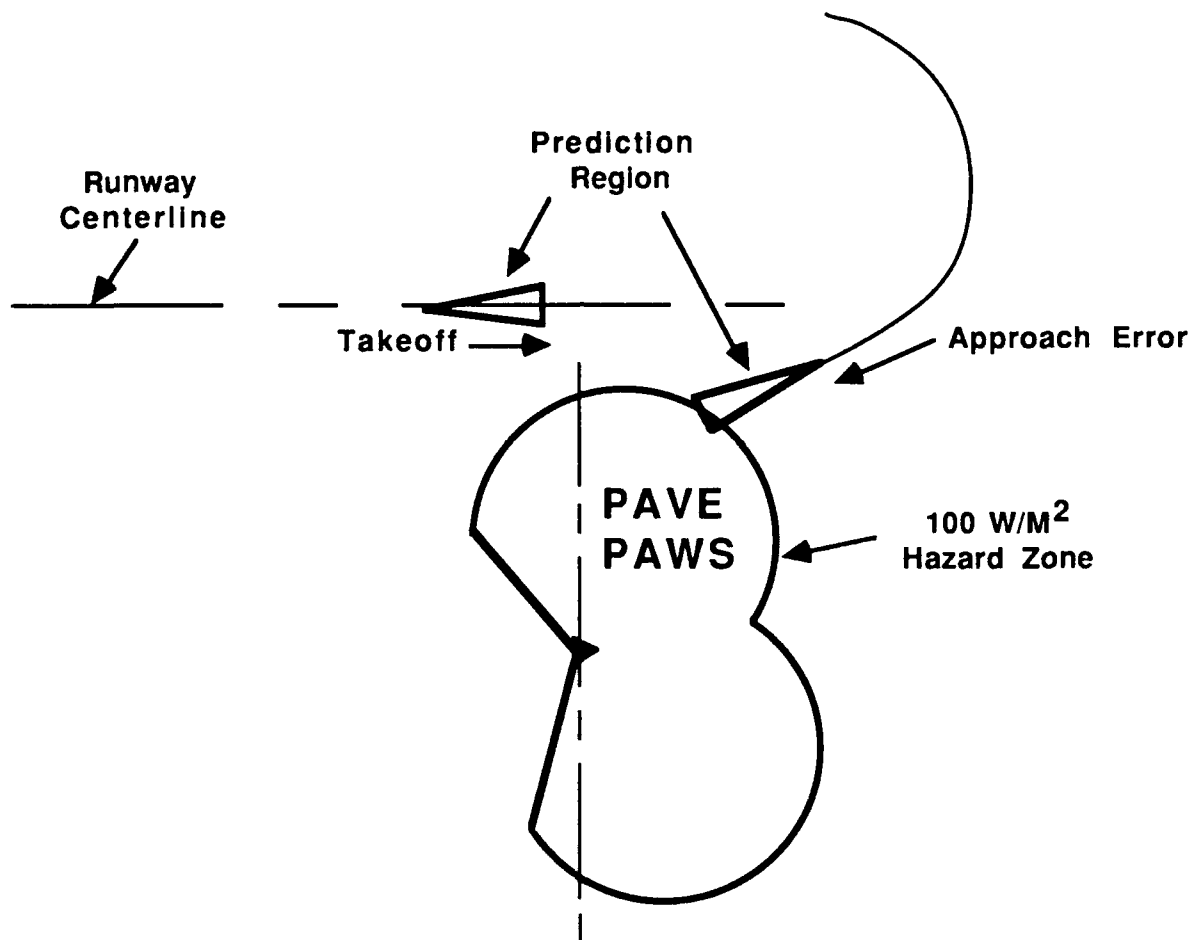
Figure 9.  Track Prediction Region

in figure 9, there would be an intersection and the face would be blanked at the moment the aircraft was predicted to be at the edge of the zone. In this case, if it is desired to blank only a small sector, rather than the entire face, the width of this sector needs to be considered. For the example of the 1-G turn discussed earlier, the width of the uncertainty area would be 800 ft. For an aircraft at the edge of the hazard zone at a distance of 5300 ft. this would represent an angle as seen from the radar of 8°, so a comparatively small angular sector would need to be blanked. Of course, this angular width would have to be increased as the aircraft came closer to PAVE PAWS.

Thus far, we have discussed the uncertainties in the prediction relevant to what the aircraft itself could do in the interval between scans. Now we will discuss the uncertainties in the position resulting from errors in the ASR/beacon measurements themselves. The ASR/beacon employs built-in test and calibration to maintain accuracy. For instance, a fixed passive echo is used to calibrate the ASR timing and accuracy, while a transponder is used to calibrate the beacon. Additional calibration can be provided in the direction of PAVE PAWS by placing a passive reflector and a transponder on the PAVE PAWS roof if desired.

The range and angle errors of the ASR and beacon based on a single scan without any smoothing were given in table 6. These were used to determine how they would translate into position, heading, and velocity errors in a representative tracker. The characteristics of the tracker are derived in appendix B. The example examined here is that of an aircraft taking off on RWY 14. The position errors in the tracker computation in the down-range and cross-range dimensions are given in figures 10 and 11. They are basically smoothed values of the per-scan range and angle errors given in table 6. They are given as a function of scan time to see if this makes a significant difference. The basic scan time of the ASR/beacon is five seconds. The down-range direction is radially, or in the range direction, from the ASR/beacon, while the cross-range direction is that perpendicular to it. The latter is actually the angular error converted to feet.

The important error is the cross-range error because it is in the direction of the hazard zone, and if it became excessive it could give a false prediction that the aircraft was heading toward the zone. As shown here, it varies by a factor of about two as the scan time varies from one to five seconds, but, in either case, it is small. Figures 12 and 13 give the heading and velocity errors for an aircraft taking off on RWY 14. Again, these values are not significantly different whether the scan time is one or five seconds. The heading error for the 5-second scan time is only about 2.2°. The excursion of 200 and 400 ft. at 1500 ft., discussed earlier for maneuver prediction, represents an angular offset of about 8 and 15 degrees, respectively, so the 2.2° heading error does not add appreciably to this. In other words, this additional error would not cause false alarms by indicating that an aircraft aligned with the runway was heading toward the hazard zone. For a 5-second scan the velocity error is about 3.8 knots. For a 5-second prediction, this would amount only to about a 100-foot error. When considering sector blanking, these errors need to be considered, but they do not add substantially to the prediction area discussed earlier. Hence sufficient accuracy is available at a 5-second scan time to make a prediction five seconds ahead, without causing extraneous alarms, and to use sector blanking rather than face blanking if necessary to minimize the impact on the mission.
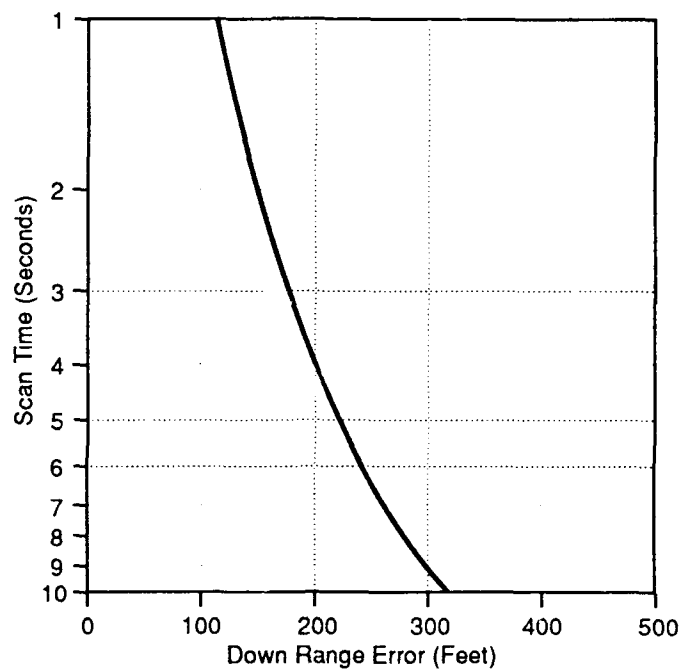
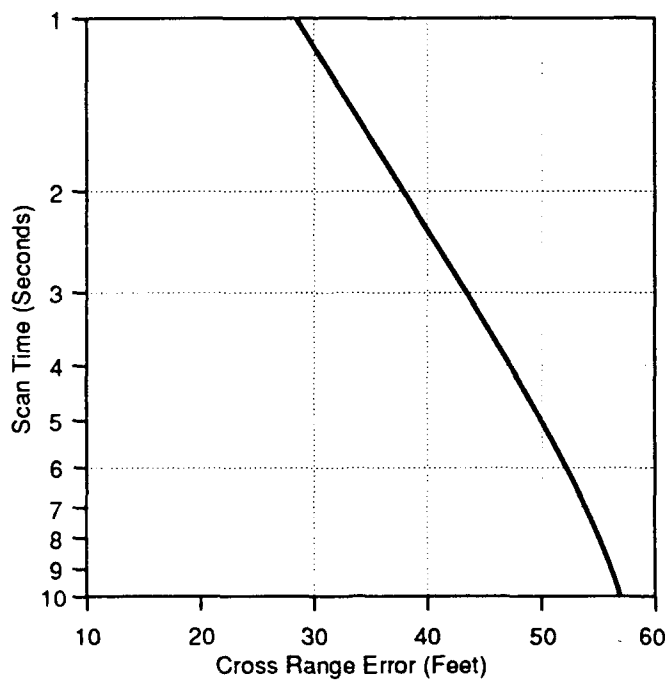Figure 10. Down-Range Error versus Scan Time



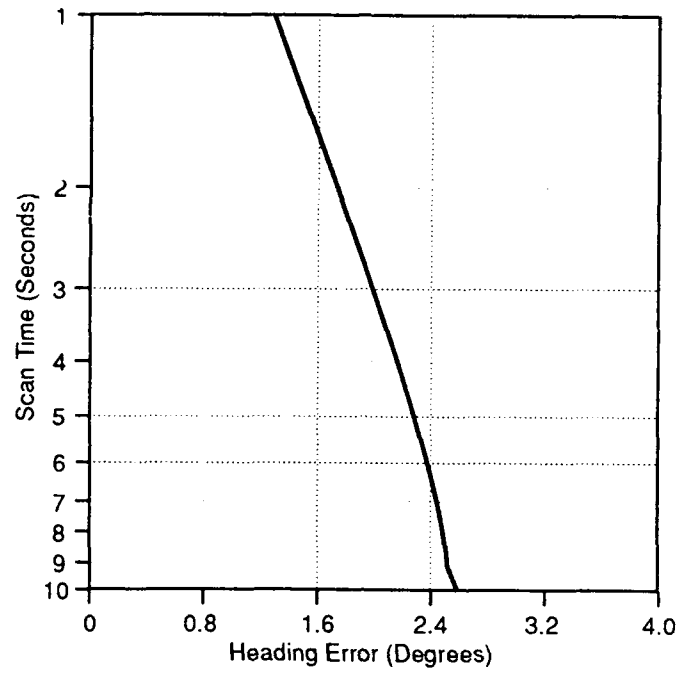Figure 11. Cross-Range Error versus Scan Time
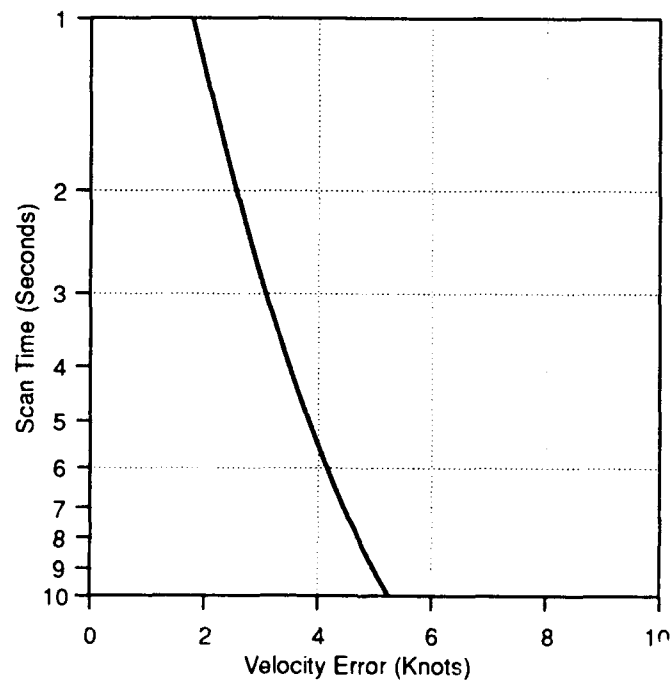
34

Figure 12. Heading Error versus Scan Time



Figure 13. Velocity Error versus Scan Time

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In addition to the short prediction time, discussed above, which takes into account worst-case target maneuverability, a longer term prediction could be made based on existing track data in an attempt to give the operator as long a warning time as possible and allow him to override the blanking command if he so desires. The most reasonable time should be decided after a test program or during DT&E but would probably be about 15 seconds. If the time is too long it could result in many false alarms since aircraft that initially appeared to be heading toward the zone may turn away. For instance, aircraft in a final turn approaching RWY 32 from the east would be heading toward the hazard zone for a portion of the turn. Typically, this would be of the order of 20 to 40 seconds before completing the turn and reaching the runway. In these cases, assuming the aircraft landed properly, a warning time longer than 15 seconds could prove to be false. The number of false warnings must be balanced against the increased time given to evaluate the possibility of penetration, and to decide whether or not to override. But again, if an aircraft not headed toward the zone suddenly made a turn toward it, then five seconds may be the most warning that is available. The blanking should be automatic unless overridden. This is because it cannot be assumed that an individual will act with the ability required to initiate a blanking action, particularly if the time is short.

## 5.5 DESCRIPTION OF IMPLEMENTATION

The block diagram of figure 14 shows the relation between the equipment in the RAPCON radar facility and the PAVE PAWS radar. The solid lines indicate the equipment that would be added. The output of the ASR and beacon would be digitized, put through modems, and sent to PAVE PAWS using phone lines. The information would be plot data, ie., range and azimuth from the ASR, and range, azimuth, altitude and other identification from the beacon. Three 2400 baud lines would be entirely adequate.

The information could also be sent via optical cable or microwave link. However, these methods are generally used where a wide bandwidth is required, and that is not the case here. The information could be encrypted, if desired, and equipment for this is available. However, it is not considered necessary because the basic information itself is not classified. At PAVE PAWS, the data would be brought into the MWOC, and put on a separate display.

The display would be fairly simple. It would consist of a map which would show the PAVE PAWS hazard area. Information such as aircraft identification and altitude would be displayed in a way similar to that presently done by an traffic control display. Track processing would be provided to minimize false reports and provide velocity and heading estimates on tracked aircraft. Vectors would be provided on the display that would show the direction of tracks. Predictions would be made of aircraft position up to about 30 seconds ahead, and if this position was found to be at or inside the hazard zone, an audible alarm would be sounded immediately, and a signal would be sent to the PAVE PAWS array when the aircraft entered. This signal would either turn off the RF drive to a face (face blanking), disable RF transmission on all beams above a given elevation angle (high beam blanking) or disable RF transmission on a certain azimuth or elevation sector. Of course, this signal could be overridden immediately if an operator so desired.

As discussed earlier, there could be cases when an aircraft makes a sudden turn toward the hazard zone and there would be very little prediction time available. In these cases, a person would not have time to react manually. This is why the interruption should be automatic. The track information would be available on the display to assist the operator in making a decision to override.

The choice of blanking technique will depend on the frequency of the penetration. Face blanking would be the simplest and least expensive to implement because it would not require an interface with the software. It would consist simply of inhibiting the RF drive to a face. Blanking of a sector of beams could also be used but it would require an interface with the PAVE PAWS software and would be more expensive. A simple version of sector blanking (high beam blanking) would consist of blanking the upper set of beams such as, for instance, all those above 10°. This would be based on the premise that in the vast majority of cases the aircraft would be above 10° and blanking above 10° would leave the 3° fence and hence the Early Warning mission search capability intact. Of course, if an aircraft were below 10° either the beams below 10° would be inhibited or the face would be blanked as befc ʰ. Blanking of small sectors would be the most complex and expensive. This would consist of blanking the particular sector of beams around the aircraft.

## 5.6 EQUIPMENT AVAILABILITY

Neither the present ASR-5 nor the ASR-8, which is to replace it, has a digitizer. A digitizer is necessary in order to remote the data. The recently built ASR-9 does have a digital output, but one of these is not slated to replace the ASR-5 at Robins. The possibility of purchasing an ASR-9 for Robins should be seriously considered. Nevertheless, various digitizers could be made available. A primary candidate is the Common Digitizer (CD). This digitizer has been in use by the FAA for many years. The latest version has two channels for complete redundancy and very high reliability. It is built by Telephonic in Farmingdale, NY. The specific model for a terminal radar application is designated a CD-2. Redundant channels with automatic switchover are also employed to give extremely high reliability. Several of the CD-2s are in use and the FAA supports it. Since there are no surplus ones available, one would have to be ordered from the manufacturer. However, the new CD-2s are replacing CD-1s which will then become surplused and the appropriate version of one of these may be used at terminal radars. The CD-1 will be supportable for about 10 years. Another candidate is the Sensor Receiver and Processor (SRAP), presently used with terminal radars employing what is called an ARTS III display. ARTS III facilities are beginning to have ASR-5 through ASR-8 radars replaced by new ASR-9 radars. This is to be done shortly at Salt Lake City and Orlando. Since the ASR-9 contains an integral digital processor, the SRAP becomes surplus in these locations. The SRAP normally has a parallel data interface and this would have to be converted to a serial interface using a board made by Unisys.

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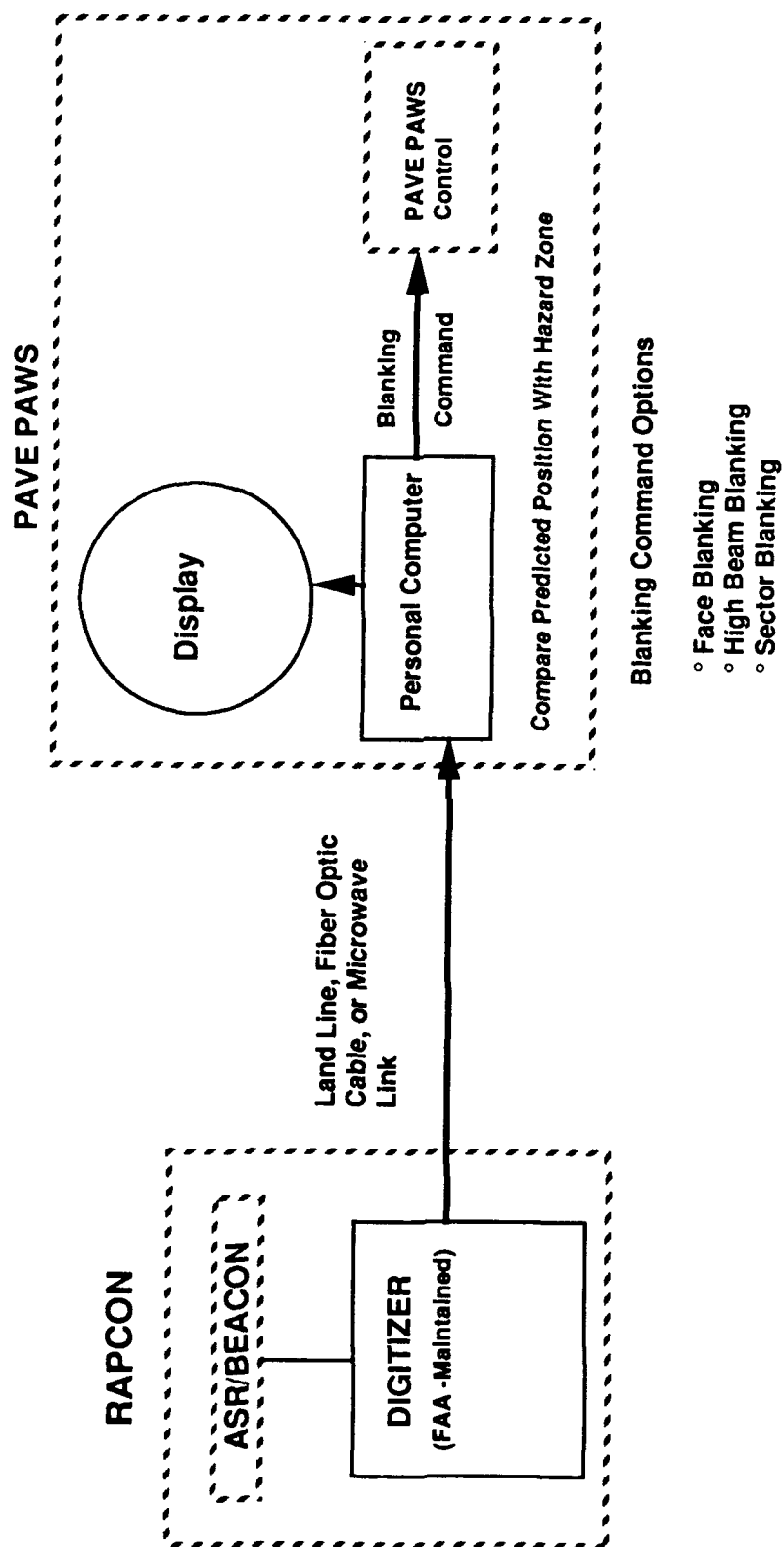
Figure 14. Implementation of Approach

Another digitizer made by Litton is called the Radar Beacon Digitizer (RBD). This is designated the CV-3682 and is being used in US Navy FACSFAC locations as well as in some customs radar installations. Litton also has a combined digitizer and tracker, or Advanced Tracking System (ATS), designated the AN/GYQ-51, which is being used in various applications. But these last two units may not be supportable by the FAA and, for this reason, may not be a viable option unless an agreement could be worked out whereby either the FAA or the Air Force maintained it. Of course, the maintenance requirements on these units would be minimal. If it were only necessary to use beacon information, an even wider array of equipments would be available. However, it is assumed here that it is desirable to have the ASR returns available along with the beacon information, and the digitizer must process both sources.

As to the display, various sources are available. As stated previously, it is important to utilize some track processing to minimize false alarms and to provide a prediction, if only for a few seconds ahead. Several companies make displays which include tracking software. These include the Hughes TRACVIEW and the Sanders STARCON II. Both accept radar plot messages, process data in similar-sized equipment, and display tracks and untracked plots on a color monitor. In either case, the processor is essentially a personal computer. They will display the tracks along with beacon information, and for this application the hazard zone and the runway could be displayed along with any other pertinent information desired. If a tracked object was in the hazard zone, or predicted to be within the zone in a few seconds, the color of its symbol could be changed and an audible alarm sounded. Also a switch closure or signal could be sent which would be used to turn off the appropriate face. In this case, the display system would have to be maintained by the personnel at PAVE PAWS but any maintenance should be minimal. Also, the units should be very reliable. The cost is low enough that an additional unit could be used on standby, if desired.

As to how the data is to be sent from the ASR/beacon to PAVE PAWS, generally, three 2400 baud lines are used. This could be done using either phone lines, fiber optic cable, or a microwave link. Encryption could be used, if desired. New encryption equipment in the form of a KG-84C can be purchased, but these will be used to replace KG-84As at PAVE PAWS, so surplus KG-84As will also be available.

## 5.7 COST ESTIMATES

The advantage of the proposed approach is that it uses the existing ASR/beacon and, hence, has minimal initial cost. What is added is a digitizer at the ASR/beacon facility and a display with its associated software at PAVE PAWS. If a new CD-2 is purchased and not combined with another order it will cost about $1M. If purchased with another FAA buy it would cost about $750K. On the other hand, if a surplus CD-1 or SRAP is available there would be only the cost of shipping it to the site and installing it. Any Operation and Maintenance (O&M) cost would be minimal. As for the display and software, this cost is estimated to be about $120K, including modifications required to customize the software. If it is desirable to have two units for redundancy and reliability, an additional unit will cost about $50K. If phone lines are used, the cost is that of leasing the lines. If it is desirable to put in a fibre opticscable, the cost of the cable, conduit, and installation is estimated at $42K. Hence, the cost depends primarily on whether a surplus digitizer is available. If a CD-1 or SRAP is available, the cost would be $150-300K. If it were necessary to buy a CD-2, the cost would be $1.2-1.3M.

Also the cost of implementing face blanking would be minimal. It would consist of interrupting the RF drive to the appropriate face, which could be done without any interaction with the software. Also, this could be implemented with minimal downtime or operational impact. On the other hand, sector blanking would be considerably more expensive since it would require an interaction with the software and would require changes to the software. The cost of this is estimated at $1-2M.

## 5.8 RESISTANCE TO JAMMING AND INTRUSION

Since the S/N is high for both the ASR and the beacon at this short range this gives a high resistance to jamming. The beacon is particularly difficult to jam because the beacon "defruiter" will tend to reject the uncorrelated noise pulses. Further, the tracking software would have a certain resistance to jamming because it would have to correlate with a specific track and would have to appear as a specific target in the hazard zone. In any case, back-up procedures similar to those in place now could be used if it appeared that an unusual amount of noise were present. For instance if a consistent amount of noise or alarms were present and this caused a face to be turned off for more than a minute, the operator at PAVE PAWS would call the tower or the RAPCON to see if an unusually large number of aircraft were present. The tower or the RAPCON could ask aircraft not to land or to stay clear of PAVE PAWS. Also, the operator at PAVE PAWS always has the option of overriding the signal to turn a face off. The display should help him to make a decision.

The use of a fiber optic cable or a telephone line with encryption at each end will help to prevent intrusion between the ASR/beacon and PAVE PAWS. Of course, this would not preclude an intruder from entering the RAPCON or the ASR/beacon facility and injecting some kind of noise or false reports into the data sent to PAVE PAWS. If this is a concern, special badges or clearances would be required. Although the present RAPCON facility being used by the ASR/beacon is at the flight line on the base, it is not a secure facility and

would be subject to intrusion. Back-up procedures could be used to minimize the detrimental effects of such intrusion. However, if this is not considered satisfactory, the facility would have to be made secure.

# SECTION 6

## MEASUREMENT AND TEST PROGRAM

A measurement program is suggested to:

1. Verify performance

2. Provide a basis for determining the number of aircraft penetrating the hazard zone per unit time

3. Evaluate blanking techniques

4. Evaluate operator requirements and man-machine interface

5. Validate functions, i.e., tracker algorithms

This could be done without interfering with PAVE PAWS operations. It could be done at little expense using FAA surplus equipment, if available, or equipment loaned or leased from a private company. For example, if a surplus CD-1 or a SRAP digitizer was available it could be used. Litton Data Systems has indicated a willingness to loan or lease their ATS, presently in government inventory, and designated the AN/GYQ-51. It is both a digitizer and a tracker. Also, both Hughes and Sanders have indicated a willingness to loan or lease a display system for a measurement program. A suggested measurement configuration is given in figure 15. For measurement purposes, the display would not have to be located at PAVE PAWS. Since the digitized information has a low bandwidth, it can be sent anywhere over phone lines. This would allow one or more displays to be located at any remote locations including ESD or MITRE Bedford. Tracks could be viewed as desired and the software could be set to record the tracks whenever there was a penetration. This could be recorded on floppy disks in a way similar to the way information from the North Warning radars is recorded at the Regional Operating Centers. Such a measurement phase would not interfere with any other operation at the RAPCON or at PAVE PAWS. At the conclusion of the measurement period the equipment could be returned.

Another interesting aspect of this approach is that more specific testing could be done without interfering with PAVE PAWS operation. For instance, planes could be flown over PAVE PAWS that were not equipped with EEDs. The system could be evaluated and the operation would be completely transparent to PAVE PAWS. Also, data from Robins AFB includes only counts of aircraft. It does not include data that might be obtained during periods of high density migratory bird flights. Tests and measurements could be performed during periods of migration in spring or fall months to determine the response of the tracker to bird flights near PAVE PAWS. The information obtained during this testing may serve to shorten the DT&E period.
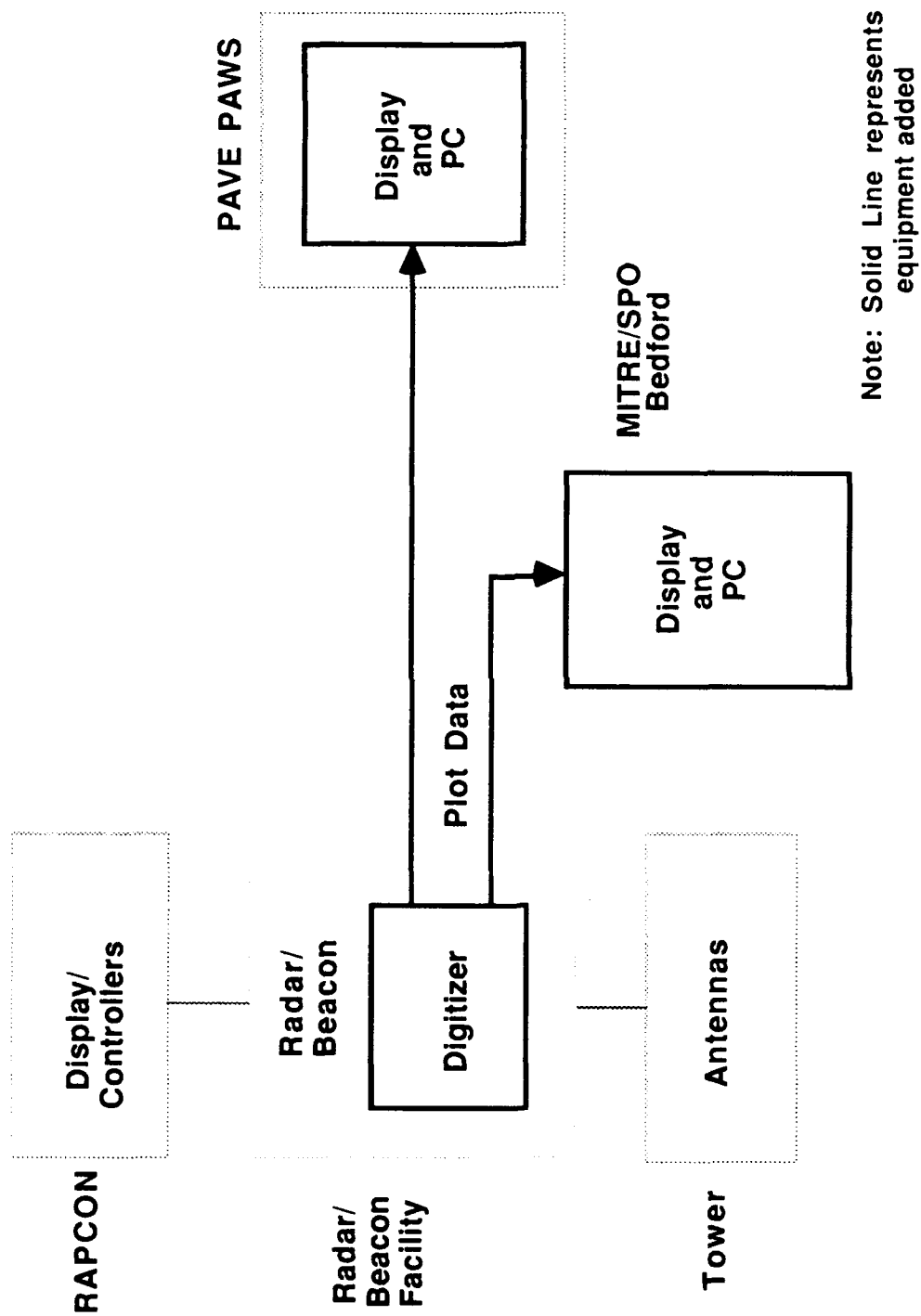
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Figure 15. Measurement Configuration

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# SECTION 7

## CONCLUSIONS

A set of requirements has been synthesized and the analysis indicates that the option of using the present ASR/beacon system at Robins AFB will meet the requirements. This system provides good coverage immediately above and around the PAVE PAWS radar. Tracking accuracy is sufficient to provide predictions of target position without causing excessive false alarms and to allow sector blanking if this becomes desirable. The redundancy provided by both the ASR and the beacon system yields a high probability of detection and high availability. The use of existing equipment affords low cost and ease of implementation. The interface with PAVE PAWS would consist of either face blanking, high beam blanking, or sector blanking, each with a different impact on the mission. Which method is chosen will depend on user requirements.

Since an aircraft can make a sudden turn toward PAVE PAWS it is not practical to always guarantee a prediction time longer than a few seconds. The blanking should be automatic because it cannot be assured that an individual will act with the reliability required. However, this command could be overridden if the PAVE PAWS operator has a higher priority task.

A measurement program is suggested. Such a program can be carried out on a non-interfering basis at minimum cost and the results could provide useful data prior to Development, Test, and Evaluation (DT&E).

# LIST OF REFERENCES

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2. DOD Flight Information Publication (En Route) IFR-Supplement United States, 8 March 1990.

3. USAF, 31 March 1978, "Explosive Safety Standards,"AF Regulation 127-100.

4. Hovan, T., 27 August 1987, "EED Assessment," Presentation Material.

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6. Maintenance Data for RAPCON at Robins AFB.

# APPENDIX A

## ASR/BEACON CALCULATIONS

For the ASR-5 the signal-to-noise ratio is calculated as follows:

$$\frac{S}{N} = \frac{P_t \tau\, G_t\, G_r \sigma \lambda^2}{(4\pi)^3\, R^4\, KT_s\, C_B\, L}$$

where

$P_t$ = Peak power transmitted

$\tau$ = Pulse duration

$G_t$ = Transmit antenna gain

$G_r$ = Receive antenna gain

$\sigma$ = Target radar cross section

$\lambda$ = Wavelength (2700 MHz)

$R$ = Range to aircraft

$K$ = Boltzmann's constant joules/oK

$T_S$ = System noise temperature

$C_B$ = Bandwidth correction factor

$L$ = Losses

In addition

$$T_s = 290 (F_n - 1) + T_a$$
$$L = L_p L_t L_g$$

where

$F_n$ = Receiver noise figure
$T_a$ = Antenna temperature
$L_p$ = Beam shape loss
$L_t$ = Plumbing losses
$L_g$ = Sensitivity time control loss

The values along with their equivalent are dB as given in table A-1.

## Table A-1. ASR-5 S/N Calculations

| Parameters | Units | +dB | -dB |
|---|---|---|---|
| $P_t$ = | 400 kW | 56 | |
| $\tau$ = | .833 μsec | | 60.8 |
| $G_t$ = | 34 dB | 34 | |
| $G_r$ = | 34 dB | 34 | |
| $\sigma$ = | 1 sq. meter | 0 | |
| $\lambda$ = | .11 meters | | 19.2 |
| $4\pi$ = | 12.6 | | 33.0 |
| $R$ = | 10 nmi | | 170.7 |
| $K$ = | $1.38 \times 10^{-23}$ | 228.6 | |
| $T_s(1)$ = | 646° | | 28.1 |
| $C_B$ = | 1.6 | | 2.0 |
| $L(2)$ = | 10.8dB | | 10.8 |
| | | 352.6 | 324.6 |
| | | 324.6 | |
| S/N = | | 28.0 | |

(1)   $F_n$ = 4.5 dB, $T_a$ = 124°K
(2)   $L_p$ = 1.6 dB, $L_t$ = 3.2 dB, $L_g$ = 6 dB

For the beacon interrogator (ATCBI-4) downlink the signal-to-noise ratio at the interrogator is calculated as follows:

$$\frac{S}{N} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 R^2 K T_s B L}$$

where

$P_t$ = Transponder peak power transmitted

$G_t$ = Transponder transmit antenna gain

$G_r$ = Interrogator receive antenna gain

$\lambda$ = Wavelength (1090 MHz)

$R$ = Range to aircraft

$K$ = Boltzmann's constant

$T_s$ = Interrogator system noise temperature

$B$ = Bandwidth

$L$ = Losses

In addition

$$T_s = 290 (F_n - 1) + T_a$$
$$L = L_r L_t L_g$$

where

$F_n$ = Receiver noise figure
$T_a$ = Antenna temperature
$L_t$ = Transponder transmit loss
$L_r$ = Interrogator receive loss including beamshape loss
$L_g$ = Sensitivity time control loss

The value along with these equivalents in dB are given in table A-2.

## Table A-2. ATCBI-4 Downlink Calculation

| Parameters | Units | +dB | -dB |
|---|---|---|---|
| $P_t$ = | 500 W | 27.0 | |
| $G_t$ = | 5.5 dB | 5.5 | |
| $G_r$ = | 21 dB | 21.0 | |
| $\lambda$ = | .275 meters | | 11.2 |
| $4\pi$ = | 12.6 | | 22.0 |
| R = | 10 nmi | | 85.3 |
| K = | $1.38 \times 10^{-23}$ | 228.6 | |
| $T_s(1)$ = | $2734^o$ | | 34.4 |
| B = | .4 MHz | | 56.0 |
| L(2) = | 32.3 dB | | $\underline{32.3}$ |
| | | $\overline{282.1}$ | 241.2 |
| | | $\underline{241.2}$ | |
| S/N = | | 40.9 | |

(1)  $F_n$ = 10 dB, $T_a$ = 124°K
(2)  $L_t$ = 5.5 dB, $L_r$ = 4.8 dB, $L_g$ = 22 dB

For the beacon interrogator (ATCBI-4) uplink, the signal-to-noise ratio at the transponder is calculated as follows:

$$\frac{S}{N} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 R^2 K T_s B L}$$

where

$P_t$ = Interrogator peak power transmitted

$G_t$ = Interrogator transmit antenna gain

$G_r$ = Transponder receive antenna gain

$\lambda$ = Wavelength (1030 MHz)

$R$ = Range to aircraft

$K$ = Boltzmann's constant joules/$^\circ$K

$T_s$ = Transponder noise temperature

$B$ = Bandwidth

$L$ = Losses

$T_s$ = 290 ($F_n$-1)

$L$ = $L_t L_r$

where

$F_n$ = Receiver noise figure

$L_t$ = Interrogator transmit loss

$L_r$ = Transponder receive loss

The values along with their equivalent in dB are given in table A-3.

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## Table A-3. ATCBI-4 Uplink Calculations

| Parameters | Units | +dB | -dB |
|---|---|---|---|
| $P_t$ = | 240 W | 23.8 | |
| $G_t$ = | 21 dB | 21.0 | |
| $G_r$ = | 5.5 dB | 5.5 | |
| $\lambda$ = | .291 | | 10.7 |
| $4\pi$ = | 12.6 | | 22.0 |
| R = | 10 nmi | | 85.3 |
| K = | $1.38 \times 10^{-23}$ | 228.6 | |
| $T_s(1)$= | $1.45 \times 10^6$ °K | | 61.6 |
| B = | .4 MHz | | 56.0 |
| L(2) = | 10.3 dB | $\overline{\phantom{278.9}}$ | $\underline{10.3}$ |
| | | 278.9 | 245.9 |
| | | $\underline{245.9}$ | |
| S/N = | | 33.0 | |

(1) $F_n$ = 37 dB
(2) $L_t$ = 5.5 dB, $L_r$ = 4.8 dB

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The signal-to-clutter ratio is calculated as follows:

$$A_c = R\theta_a \frac{C\tau}{2} \sec \psi$$

Where

$A_c$ = Area of the surface illuminated by the radar pulse

R = Range to clutter cell containing the target of interest = 10 nmi

$\theta$ = Antenna azimuth beamwidth = 1.5°

C = Velocity of propagation = $3 \times 10^8$ meters per second

$\tau$ = Pulse length = .833 μsec

$\psi$ = Grazing angle = .1°

For these values:

Ac = 60577 square meters or 47.8 dBsm

$\sigma_O$ = Reflection coefficient = -42 dB (woods and cultivated land)

$\sigma_c$ = Effective cross section = $A_c\sigma_O$ = 5.8 dBsm

If R = Cancellation ratio = 34 dB

Let C = Net clutter after cancellation = R $\sigma_c$ = -28.2 dB

S = Aircraft cross section = 1 square meter or 0 dBsm

Then S/C = 28.2 dB

The number of hits is calculated as follows:

For the ASR-5

$$M = \frac{\theta_a \, fr}{6Wr}$$

$\theta_a$   = Antenna azimuth beamwidth = 1.5°
fr    = Radar PRF = 1200 pps
Wr   = Scan rate = 12 rpm

For these values

M    = 25 hits

For the ATCBI-4

$\theta_a$   = 5° (working beamwidth at close range)
fr    = 400
Wr   = Scan rate = 12 rpm

For these values

M    = 28 hits

# APPENDIX B

# VELOCITY ESTIMATION ACCURACY

In this appendix, the performance of an optimal tracking filter utilizing groundbased radar measurements of range and azimuth to estimate aircraft velocity (speed and heading) in the landing approach and takeoff phase of flight is analyzed.

For the purpose of this analysis, aircraft motion is considered planar (ignoring altitude), hence range and azimuth uniquely determine aircraft position relative to the radar. The relative aircraft/radar geometry is illustrated in figure B-1. $\vec{r}$ and $\vec{V}$ represent the aircraft position and velocity vectors, respectively. The radar measures the aircraft range, r (magnitude of $\vec{r}$ ), and azimuth, $\theta$.

It will be convenient to represent the position and velocity vectors in the non-inertial Cartesian coordinate system, $\hat{i}$ - $\hat{j}$ (see figure B-1). This coordinate system is attached to the aircraft and has its $\hat{i}$ axis aligned along the range vector, $\vec{r}$ , and its $\hat{j}$ axis in the cross-range direction. Note that the $\hat{i}$ - $\hat{j}$ system rotates with an angular velocity given by

$$\vec{\omega} = \dot{\theta}\,\hat{k} \qquad (\text{where } \hat{k} = \hat{i} \times \hat{j}) \qquad (1)$$

The aircraft range and velocity vectors are expressible in the $\hat{i}$ - $\hat{j}$ system as

$$\vec{r} = r\,\hat{i} \qquad (2)$$

and

$$\vec{V} = \dot{r}\,\hat{i} + r\,\dot{\theta}\,\hat{j} \qquad (3)$$

For compactness of notation we will write the along-range and cross-range components of velocity as

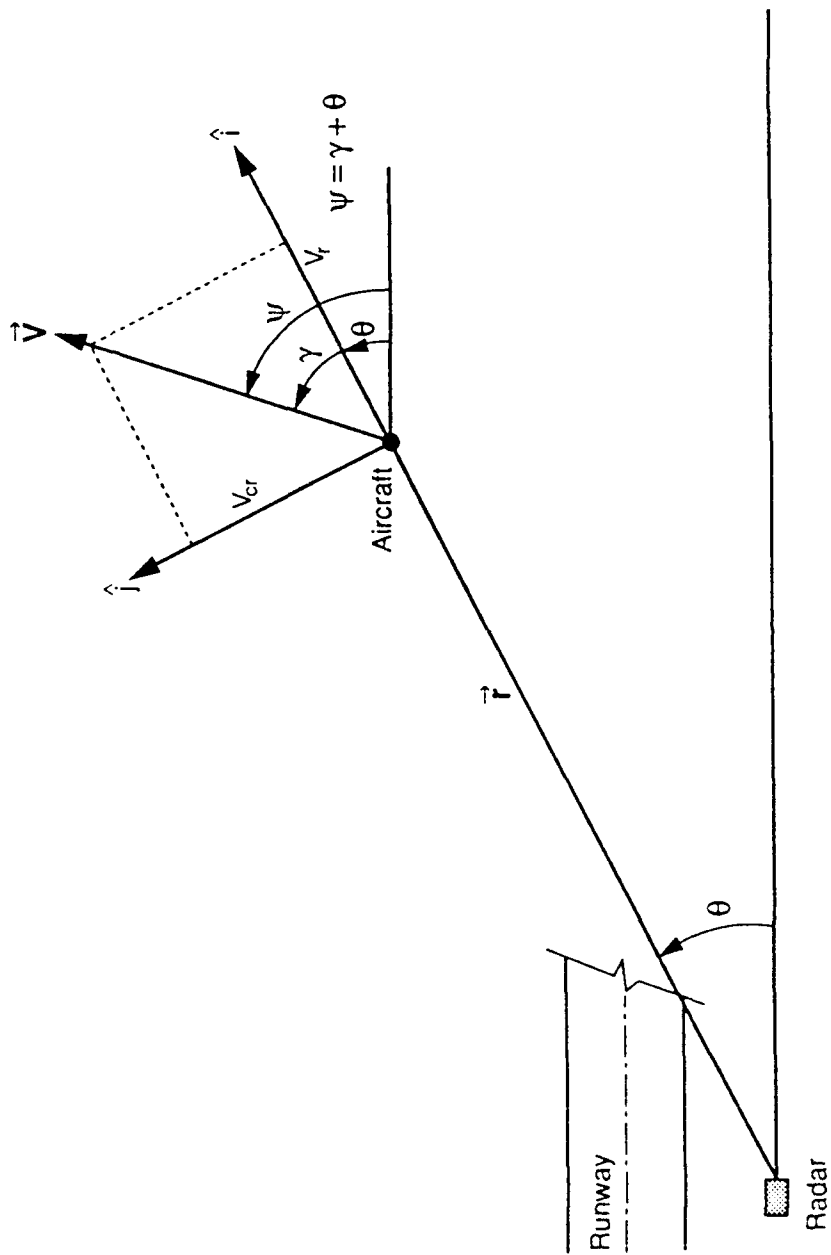$$V_r = \dot{r} \qquad (4)$$

and

Figure B-1. Geometry of Aircraft Position Relative to the Radar

$$V_{cr} = r\,\dot{\theta} \,, \tag{5}$$

respectively. We note that the flight path angle, $\gamma$, measured with respect to the $\hat{\imath}$ axis (see figure B-1), can be expressed in terms of the velocity components as

$$\gamma = \tan^{-1}\left(\frac{V_{cr}}{V_r}\right) \tag{6}$$

Let us assume that about a nominal aircraft state $(r_0, \theta_0, \dot{r}_0, \dot{\theta}_0)$ there exists random state perturbations $(\delta r_0, \delta\theta_0, \delta\dot{r}_0, \delta\dot{\theta}_0)$ due in part to measurement noise and unknown maneuver accelerations. These random state perturbations give rise to random perturbations in the along-range and cross-range components of velocity denoted by $\delta V_r$ and $\delta V_{cr}$, respectively. Linearizing equations (4) and (5) about the nominal state, we obtain the following expressions for $\delta V_r$ and $\delta V_{cr}$:

$$\delta V_r = \delta\dot{r} \tag{7}$$

$$\delta V_{cr} = r_0\,\delta\dot{\theta} + \dot{\theta}_0\,\delta r \tag{8}$$

Assuming no cross correlation between range and azimuth perturbations (and their rates), the variances for $\delta V_r$ and $\delta V_{cr}$, i.e., $\sigma^2_{\delta V_r}$ and $\sigma^2_{\delta V_{ci}}$, respectively, as computed from equations (7) and (8) are

$$\sigma^2_{\delta V_r} = \sigma^2_{\delta\dot{r}} \tag{9}$$

$$\sigma^2_{\delta V_{cr}} = r_0^2\,\sigma^2_{\delta\dot{\theta}} + \dot{\theta}_0^2\,\sigma^2_{\delta r} \tag{10}$$

The variance terms on the right-hand sides of equations (9) and (10) represent the range, range rate, and azimuth rate estimation accuracies that one would obtain from a track filter processing radar range and azimuth measurements. For the purpose of this analysis, a simple two-state Kalman filter model of the form described in reference B-1 will be used to filter range and azimuth measurements. Specifically, a bank of two of these Kalman filters,

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operating in parallel, separately processes the range and azimuth measurements to generate optimal estimates for ($\delta r, \delta \dot{r}$) and ($\delta \theta, \delta \dot{\theta}$), respectively.[1] Further, it is assumed that the Kalman filters have reached steady state operation so that their gains are constant. Under this condition, the Kalman filter model reduces to the familiar $\alpha$ - $\beta$ tracker.

The optimal $\alpha$ - $\beta$ gain relationships are developed in reference B-1 and can be expressed in terms of a dimensionless parameter, called the tracking index, $\Lambda$, which is a function of the measurement update period, T, measurement noise, $\sigma_m$, and aircraft maneuver acceleration noise, $\sigma_w$. These relationships are summarized in equations (11a)-(11c)

$$\Lambda = \frac{T^2 \sigma_w}{\sigma_m} \tag{11a}$$

$$\Lambda^2 = \frac{\beta^2}{1-\alpha} \tag{11b}$$

$$\beta = 2(2 - \alpha) - 4\sqrt{1 - \alpha} \tag{11c}$$

Let $\sigma_{w_\theta}$ and $\sigma_{m_\theta}$ , and $\sigma_{w_r}$ and $\sigma_{m_r}$ represent the azimuth and range maneuver noise and measurement noise, respectively. Using equations (11a)-(11c), the gains for the azimuth $\alpha$ - $\beta$ tracker, $\alpha_\theta$ and $\beta_\theta$, and the range $\alpha$ - $\beta$ tracker, $\alpha_r$ and $\beta_r$, can be parametrically expressed in terms of the tracking index as

$$\Lambda_\theta = \frac{T^2 \sigma_{w_\theta}}{\sigma_{m_\theta}} \tag{12a}$$

$$\Lambda_\theta^2 = \frac{\beta_\theta^2}{1 - \alpha_\theta} \tag{12b}$$

---

[1] The range and azimuth measurements are assumed to be decoupled.

$$\beta_\theta = 2(2 - \alpha_\theta) - 4\sqrt{1 - \alpha_\theta} \tag{12c}$$

and

$$\Lambda_r = \frac{T^2 \sigma_{w_r}}{\sigma_{m_r}} \tag{13a}$$

$$\Lambda_r^2 = \frac{\beta_r^2}{1 - \alpha_r} \tag{13b}$$

$$\beta_r = 2(2 - \alpha_r) - 4\sqrt{1 - \alpha_r} \tag{13c}$$

As evident from the above equations, the optimal $\alpha$ - $\beta$ gains are nonlinearly related to the tracking index.

The steady state estimation performance of the two optimal $\alpha$ - $\beta$ trackers in generating estimates of $(\delta\theta, \dot{\delta\theta})$ and $(\delta r, \dot{\delta r})$ from noisy measurements of range and azimuth is found in reference B-1.

$$\sigma_{\delta\theta}^2 = \alpha_\theta \, \sigma_{m_\theta}^2 \tag{14a}$$

$$\sigma_{\dot{\delta\theta}}^2 = \frac{(2\alpha_\theta - \beta_\theta) \beta_\theta}{2(1 - \alpha_\theta) \, T^2} \, \sigma_{m_?}^2 \tag{14b}$$

$$\sigma_{\delta r}^2 = \alpha_r \, \sigma_{m_r}^2 \tag{15a}$$

$$\sigma_{\dot{\delta r}}^2 = \frac{(2\alpha_r - \beta_r) \beta_r}{2(1 - \alpha_r) \, T^2} \, \sigma_{m_r}^2 \tag{15b}$$

Substituting the appropriate equations from (14a-b) and (15a-b) into equations (9) and (10) yields the following along-range and cross-range velocity estimation accuracy relationships:

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$$\sigma^2_{\delta V_r} = \frac{(2\alpha_r - \beta_r)\,\beta_r}{2(1-\alpha_\theta)\,T^2}\,\sigma^2_{m_r}$$

(16)

$$\sigma^2_{\delta V_\alpha} = \frac{r_0^2\,(2\alpha_\theta - \beta_\theta)\,\beta_\theta}{2(1-\alpha_\theta)\,T^2}\,\sigma^2_{m_\theta} + \dot\theta_0^2\,\alpha_r\,\sigma^2_{m_r}$$

(17)

With equations (16) and (17), the relationships between speed and heading estimation accuracy, and radar measurement accuracies can now be derived. Examining speed, V, first, we note that

$$V = \sqrt{V_r^2 + V_{cr}^2}$$

(18)

Linearizing equation (18) about the nominal velocity $(V_{r_0}, V_{cr_0})$ gives

$$\delta V = \frac{V_{r_0}}{V_0}\,\delta V_r + \frac{V_{\alpha_0}}{V_0}\,\delta V_{cr}$$

(19)

where $\delta V$ is the speed perturbation due to random perturbations in the along-range and cross-range velocity components and $V_0 = \sqrt{V_{r_0}^2 + V_{cr_0}^2}$ . The variance for $\delta V$ as computed from equation (19) is

$$\sigma^2_{\delta V} = \left(\frac{V_{r_0}}{V_o}\right)^2 \sigma^2_{\delta V_r} + \left(\frac{V_{\alpha_0}}{V_o}\right)^2 \sigma^2_{\delta V_\alpha} + \frac{2V_{\alpha_o}V_{r_0}}{V_o^2}\,\sigma^2_{\delta V,\delta V_\alpha}$$

(20)

The cross covariance term $\sigma^2_{\delta V,\delta V_\alpha}$ in equation (20) can be computed from equations (7) and (8) to yield

$$\sigma^2_{\delta V,\delta V_\alpha} = r_0\,\sigma^2_{\delta r \delta\theta} + \dot\theta_0\,\sigma^2_{\delta r \delta r}$$

(21)

Assuming no cross correlation between the range rate and azimuth rate perturbations, the first term on the right hand side of equation (21) vanishes so that

$$\sigma^2_{\delta V_r \delta V_\alpha} = \dot{\theta}_o \, \sigma^2_{\delta \dot{r} \delta r} \tag{22}$$

The range rate and range perturbation estimate cross covariance is given by reference B-1

$$\sigma^2_{\delta \dot{r} \delta r} = \frac{\beta_r}{T} \, \sigma^2_{m_r} \tag{23}$$

Therefore,

$$\boxed{\sigma^2_{\delta V_r \delta V_\alpha} = \frac{\dot{\theta}_o \, \beta_r}{T} \, \sigma^2_{m_r}} \tag{24}$$

Recapitulating, by substituting equations (16), (17), and (24) into equation (20), we have derived an expression relating speed estimation accuracy to the steady state estimation error covariances of a set of optimal $\alpha$ - $\beta$ trackers, processing noisy range and azimuth measurements.

Turning now to the question of heading estimation accuracy, we note from figure B-1 that aircraft heading, $\psi$, is expressible as

$$\psi = \gamma + \theta = \tan^{-1}\left(\frac{r\dot{\theta}}{\dot{r}}\right) + \theta \tag{25}$$

Linearizing equation (25) about the nominal state $(r_0, \theta_0, \dot{r}_0, \dot{\theta}_0)$ gives

$$\delta\psi = \frac{1}{1 + \left(\frac{r_0\dot{\theta}_0}{\dot{r}_0}\right)^2}\left[\frac{\dot{\theta}_0}{\dot{r}_0}\,\delta r + \frac{r_0}{\dot{r}_0}\,\delta\dot{\theta} - \frac{r_0\dot{\theta}_0}{\dot{r}_0^2}\,\delta\dot{r}\right] + \delta\theta \tag{26}$$

where $\delta\psi$ is the random heading perturbation. The variance for $\delta\psi$ can be calculated from equation (26) which after some algebraic manipulation and simplification becomes

$$\boxed{\sigma_{\delta\psi}^2 = \frac{V_{r_0}^2}{V_0^2}\left\{\frac{1}{V_0^2}\left[\sigma_{\delta V_\alpha}^2 + \left(\frac{V_{\alpha_0}}{V_{r_0}}\right)^2\sigma_{\delta V_r}^2 - 2\left(\frac{V_{\alpha_0}}{V_{r_0}}\right)\sigma_{\delta V_\alpha \delta V_r}^2\right] + 2\left(\frac{r_0}{\dot{r}_0}\right)\sigma_{\delta\theta\delta\dot{\theta}}^2\right\} + \sigma_{\delta\theta}^2} \tag{27}$$

where

$$V_{r_0} = \dot{r}_0 \tag{28a}$$

$$V_{\alpha_0} = r_0\,\dot{\theta}_0 \tag{28b}$$

$$V_0 = \sqrt{\dot{r}_0^2 + (r_0\,\dot{\theta}_0)^2} \tag{28c}$$

$$\sigma_{\delta\theta\delta\dot{\theta}}^2 = \frac{\beta_\theta}{T}\,\sigma_{m_\theta}^2 \tag{28d}$$

Equation (27) in conjunction with equations (14a), (16), (17), and (24), therefore, represents the heading estimation accuracy obtainable from range, azimuth, and their respective rate estimates generated by a pair of optimal $\alpha$–$\beta$ trackers, filtering range and azimuth measurements.

Let us now adapt the above speed and heading accuracy results to the landing and takeoff scenario under investigation. The final approach geometry for the landing scenario is illustrated in figure B-2. In this scenario, the aircraft flies a final approach path parallel to the
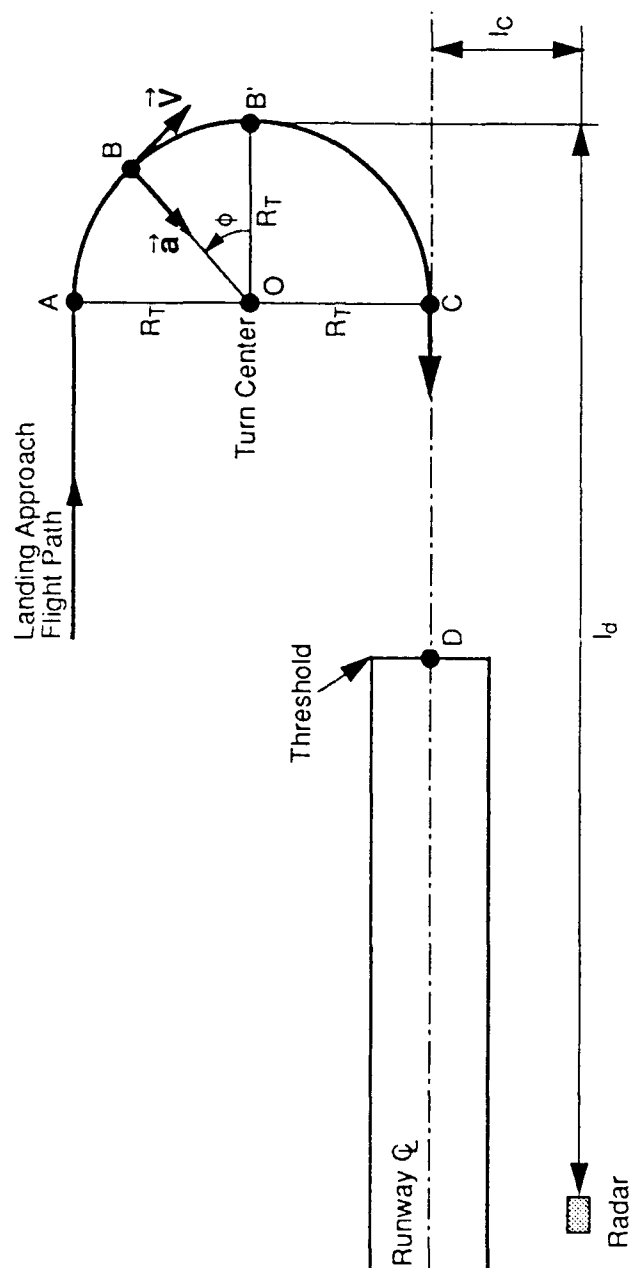
Figure B-2. Landing Approach Flight Geometry

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extended runway centerline, and laterally offset from it by a distance $2R_T$, where $R_T$ is the turn radius. At point A it initiates a circular turn and terminates it at point C when it intercepts the glideslope. As it banks out of its turn at point C, its heading is aligned along the extended runway centerline. The landing scenario is characterized by the parameters in table B-1.

### Table B-1. Landing Scenario Parameters

| __Parameter__ | __Description__ | __Nominal Value__ |
|---|---|---|
| $l_d$ | distance parallel to the runway from the radar to point B' (see figure B-2) | 25,000 ft. |
| $l_c$ | lateral offset of the radar from the runway centerline | 1,800 ft. |
| $V_0$ | nominal aircraft speed | 180 kts |
| k | turn maneuver acceleration | 0.5 gs |
| $\sigma_{m_l}$ | range measurement noise | 0.125 nmi |
| $\sigma_{m_\theta}$ | azimuth measurement noise | 0.175° |
| T | measurement update period | $1 < T < 10$ sec |

The aircraft speed and heading estimation accuracy at any point on the circular path is determined as follows. The aircraft position at some arbitrary point B on the circular path is completely specified by polar coordinates centered about the turn center O, namely $R_T$ and $\phi$. The angle $\phi$ is measured from an axis parallel to the extended runway centerline line passing through points O and B'. Since the aircraft is executing a circular turn we also note that it experiences an acceleration $\vec{a}$ directed radially inwards at point B and whose velocity $\vec{V}$ is perpendicular to $\vec{a}$ (see figure B-2). These two facts combined with the data in table B-1 allow us to compute speed and heading estimation accuracy at point B with the following algorithm.

1. Compute turn radius $R_T$.

$$R_T = \frac{V_o^2}{k\,g} \qquad \text{(g = gravitational acceleration)} \tag{29}$$

**2.** Compute nominal aircraft heading $\psi_o$ at point B.

$$\psi_o = \phi - \frac{\pi}{2} \tag{30}$$

**3.** Compute nominal state $(r_0, \theta_0, \dot{r}_0, \dot{\theta}_0)$ at point B.

$$r_o = \sqrt{[l_d - (R_T - R_T\cos\phi)]^2 + [l_c + (R_T + R_T\sin\phi)]^2} \tag{31}$$

$$\theta_o = \tan^{-1}\left(\frac{l_c + R_T}{l_d}\right) \tag{32}$$

$$\dot{r}_o = V_o \cos(\psi_o - \theta_o) \tag{33}$$

$$\dot{\theta}_o = \frac{V_o \sin(\psi_o - \theta_o)}{r_o} \tag{34}$$

Note that $V_{r_o} = \dot{r}_o$ and $V_{cr_o} = r_o\,\dot{\theta}_o$

**4.** Determine azimuthal and range acceleration, $\ddot{\theta}$ and $\ddot{r}$, respectively, of the aircraft at point B. At point B the aircraft experiences a centripetal acceleration, $\vec{a}$, of magnitude kg that is radially directed towards the turn center and is perpendicular to the velocity vector (see figure B-2). The acceleration vector $\vec{a}$ can be decomposed into an along-range and cross-range component, $a_r$ and $a_{cr}$, respectively, to give

$$a_r = -k\,g\cos(\phi - \theta_o) \tag{35}$$

and

$$a_{cr} = -k\,g\sin(\phi - \theta_o). \tag{36}$$

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From reference B-2 we know that $a_r$ and $a_{cr}$ can be expressed as

$$a_r = \ddot{r} - r\dot{\theta}^2 \qquad (37)$$

and

$$a_{cr} = r\ddot{\theta} + 2\dot{r}\dot{\theta} \qquad (38)$$

Evaluating equations (37) and (38) at $(r_0, \theta_0, \dot{r}_0, \dot{\theta}_0)$, equating them to equations (35) and (36), respectively, and solving for $\ddot{\theta}$ and $\ddot{r}$ gives us the point B azimuthal and range acceleration

$$\ddot{\theta}_o = \frac{-k\, g \sin(\phi - \theta_o) - 2\dot{r}_o\dot{\theta}_o}{r_o} \qquad (39)$$

$$\ddot{r}_o = r_o\dot{\theta}_o^2 - k\, g \cos(\phi - \theta_o) \qquad (40)$$

5. Set azimuth and range maneuver noise, $\sigma_{w_\theta}$ and $\sigma_{m_r}$, equal to the absolute values of the point B azimuthal and range acceleration computed in step 4, i.e.,

$$\sigma_{w_\theta} = \left|\ddot{\theta}_o\right| \qquad (41)$$

$$\sigma_{w_r} = \left|\ddot{r}_o\right| \qquad (42)$$

6. Determine $\alpha$, $\beta$ gains for the azimuth and range tracker from equations (12a)-(12c) and (13a)-(13c), respectively.

7. Evaluate $\sigma_{\delta V_r}^2$ from equation (16).

8. Evaluate $\sigma_{\delta V_{c_l}}^2$ from equation (17).

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**9.** Evaluate $\sigma^2_{\delta V, \delta V_a}$ from equation (24).

**10.** Compute $\sigma^2_{\delta V}$ from equation (20).

**11.** Compute $\sigma^2_{\delta \psi}$ from equation (27).

Let us turn now to the task of estimating velocity in a takeoff scenario. The nominal state about which we are interested in estimating velocity corresponds to the instant that the aircraft overflies the runway threshold on its takeoff run. This position is denoted by point D in figure B-2. For simplicity, we shall assume that the aircraft at point D has a) achieved its takeoff speed and is not accelerating, and b) has a heading co-aligned with the extended runway centerline.

The aforementioned takeoff scenario can be considered a special case of the landing approach scenario. Namely, by modifying a subset of the landing scenario parameters to the values indicated in table B-2 we have, in essence, the takeoff scenario. Thus, the algorithm used to generate the speed and heading estimation accuracy results for the landing case is equally applicable to the takeoff case.

**Table B-2. Takeoff Scenario Parameters[1]**

| Parameter | Description | Value |
|-----------|-------------|-------|
| $l_d$ | longitudinal distance from the radar to point B' | 9,500 ft. |
| V0 | nominal aircraft speed | 110 kts |
| k | maneuver acceleration | 0 gs |
| $R_T$ | turn radius | set to 0 |
| $\phi$ | polar angle of point B | 90° |

The algorithm described above was implemented on a computer, and speed and heading estimation accuracy results were generated for measurement update periods ranging from 1 second to 10 seconds for both the landing approach and takeoff scenario. These results are discussed in Section 5.4.

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[1] All other parameters remain the same as in TABLE B-1.

# LIST OF REFERENCES

B-1. Kalata, P. R., March 1984, *The Tracking Index: A Generalized Parameter for* $\alpha$ - $\beta$ *and* $\alpha$ - $\beta$ - $\gamma$ *Target Trackers,* IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-20, No. 2.

# APPENDIX C

## MANEUVER REACHABILITY SET

An issue of concern in this investigation is the likelihood of an aircraft penetrating the EED hazard zone in $t_p$ seconds if a lateral maneuver is initiated. Assuming that the aircraft is initially travelling in a constant-speed, straight-line path, we would like to determine the set of all reachable lateral position states by an aircraft executing a circular turn maneuver of duration $t_p$ or less, and of acceleration magnitude between some upper and lower bound. We shall term this set of reachable lateral states surrounding the aircraft as the maneuver reachability set. The intersection of the maneuver reachability set with the EED hazard zone could possibly be used as a criterion for commanding a momentary radar shutdown. This appendix describes the construction of the maneuver reachability set.

Figure C-1 illustrates the basic geometry of the maneuver reachability set. Given a certain aircraft speed, $V_0$, maximum and minimum turn acceleration, $+k_{max}$ and $-k_{max}$, respectively, and penetration time, $t_p$, the shaded area in figure C-1 is constructed as follows. The basic idea is to determine all the lateral positions swept out in time $t_p$ by an aircraft following a circular path with radial turn acceleration k (expressed in gs) bounded by $-k_{max} \leq k \leq +k_{max}$. The simplest means of doing this is to determine the circular arc traversed in $t_p$ for a given maneuver acceleration k which is equivalent to determining the angle $\theta_p$ it subtends (see figure C-1).

$\theta_p$ is computed from

$$\theta_p = \dot{\theta} \, t_p \tag{1}$$

where the turn rate $\dot{\theta}$ is given by

$$\dot{\theta} = \frac{k \, g}{V_o} \qquad \text{(g = gravitational acceleration)} \tag{2}$$
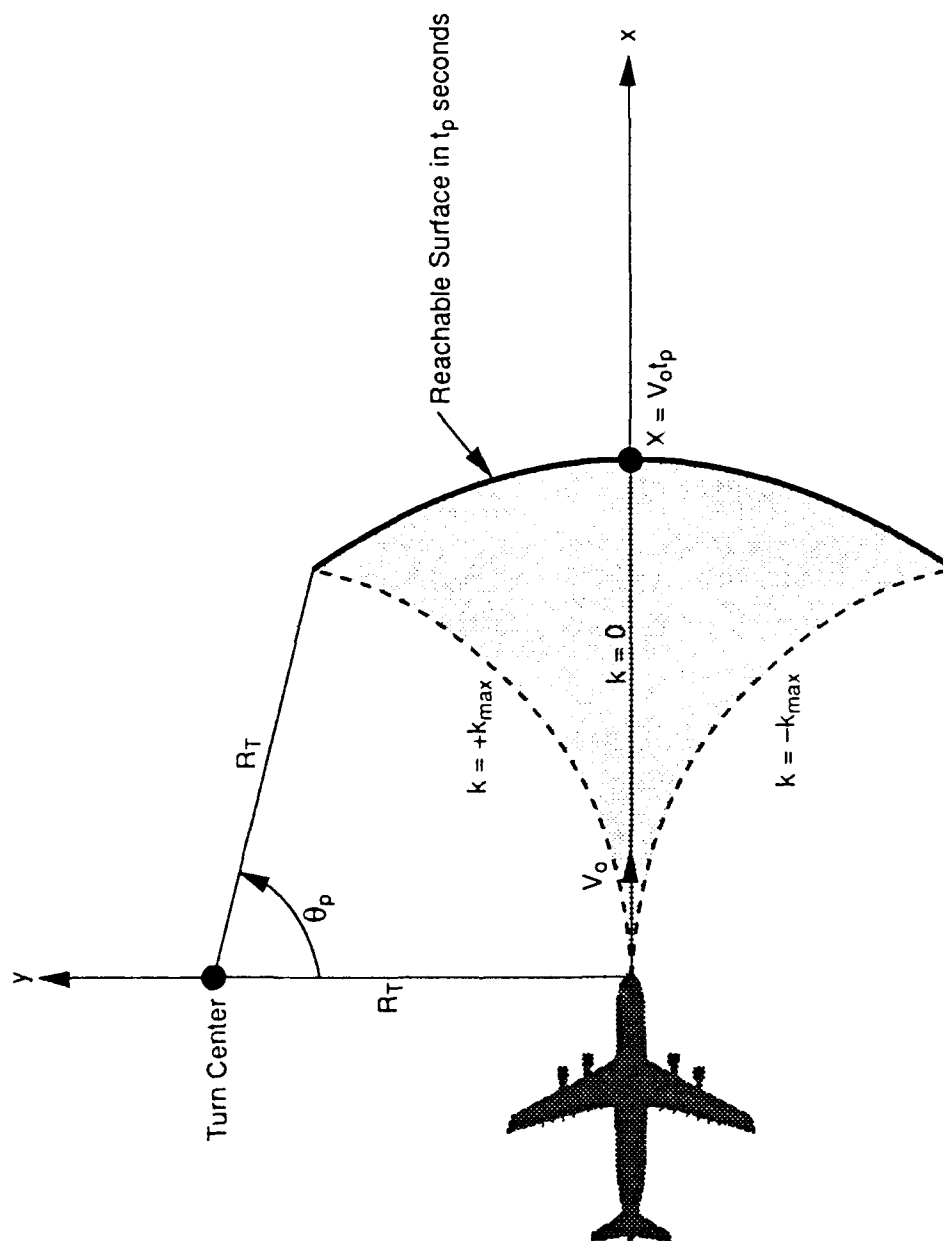
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Figure C-1. Maneuver Reachability Set Surrounding Aircraft in a Plane

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Thus, in $t_p$ seconds the coordinates of the aircraft in the x-y frame of figure C-1 are

$$x = R_T \sin \theta_p \tag{3}$$

$$\text{if } \theta_p \leq \frac{\pi}{2} \text{ and } k \neq 0$$

$$y = R_T - R_T \cos \theta_p \tag{4}$$

where the turn radius $R_T$ is equal to

$$R_T = \frac{V_o}{\dot{\theta}} \tag{5}$$

Equations (3) and (4), therefore, parametrically define (with k varying from $-k_{max}$ to $+k_{max}$) the rightmost boundary of the maneuver reachability set as depicted by the thick solid line in figure C-1. The upper and lower boundaries of the maneuver reachability set (dashed lines in figure C-1) correspond to the circular path followed by an aircraft turning with a $k = + k_{max}$ and $k = -k_{max}$ radial acceleration, respectively.

We make note of two special situations at this point. First if $k = 0$, implying that the aircraft maintains straight line constant speed flight, equations (3) and (4) are replaced by

$$x = V_o t_p \tag{6}$$

$$\text{if } k = 0$$

$$y = 0 \tag{7}$$

Secondly, if $\theta_p \geq \frac{\pi}{2}$, the aircraft could achieve maximum lateral distance by banking out of the turn when $\theta = \frac{\pi}{2}$, and flying straight instead of continuing to turn. Thus, the aircraft would fly a circular turn up till time $\frac{\pi}{2\dot{\theta}}$ when $\theta = \frac{\pi}{2}$ and then fly straight until $t_p$. In this case, equations (3) and (4) would be replaced by

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$$x = R_T \qquad\qquad \text{(8)}$$

$$\text{if} \quad \theta_p > \frac{\pi}{2} \quad \text{and} \quad k \neq 0$$

$$y = R_T + V_O \left( t_p - \frac{\pi}{2\dot{\theta}} \right) \qquad\qquad \text{(9)}$$

Figures C-2 and C-3 show the maneuver reachability set for a case where $V_O = 180$ knots, $k_{max} = 0.5$, $t_p = 5$ seconds, and $V_O = 180$ knots, $k_{max} = 1.0$, and $t_p = 5$ seconds, respectively.
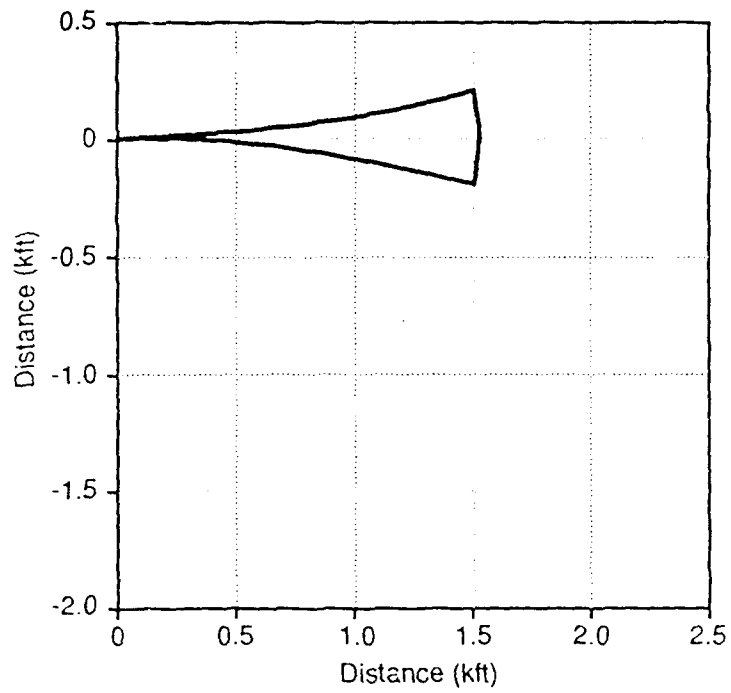
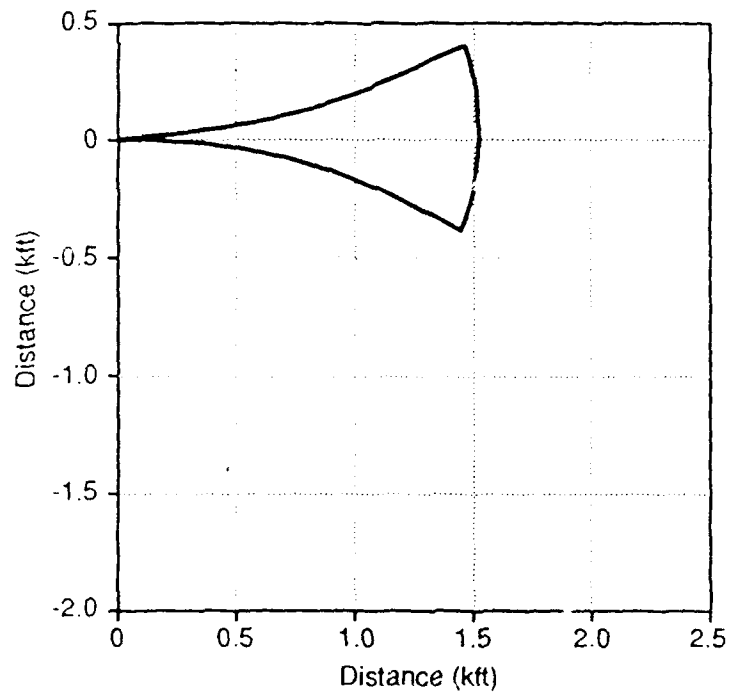Figure C-2. Maneuver Reachability Set ( $V_O$ = 180 kts, $k_{max}$ = .5, $t_p$ = 5 sec)



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Figure C-3 Maneuver Reachability Set ( $V_O$ = 180 kts, $k_{max}$ = 1, $t_p$ = 5 sec)

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# GLOSSARY

| | |
|---|---|
| ARTCC | Airport Radar Traffic Control Center |
| ASR | airport surveillance radar |
| ATA | airport traffic area |
| ATCBI | airport traffic control beacon interrogator |
| ATS | advanced tracking system |
| ATIS | automatic terminal information system |
| | |
| CD | common digitizer |
| | |
| DT&E | development test and engineering |
| | |
| EED | electroexplosive devices |
| ET | embedded tracker |
| | |
| ICBM | intercontinental ballistic missile |
| IFR | instrument flight rules |
| ILS | instrument landing system |
| IOW | interim operational workaround |
| | |
| MEA | minimum enroute altitude |
| MSL | mean sea level |
| MTI | moving target indication |
| MWOC | Missile Warning Operations Center |
| | |
| O&M | operations and maintenance |
| | |
| PPR | prior permission required |
| PRF | pulse repetition frequency |
| | |
| RAPCON | radar approach control |
| RBD | radar beacon digitizer |
| RWY | runway |
| | |
| S/C | signal-to-clutter ratio |
| S/N | signal-to-noise ratio |
| SLBM | sea launched ballistic missile |
| SRAP | sensor receiver and processor |
| | |
| TRSA | terminal radar service area |
| | |
| VFR | visual flight rules |